

Volume 15

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Number 11

BULLETIN
of the
**American Association of
Petroleum Geologists**

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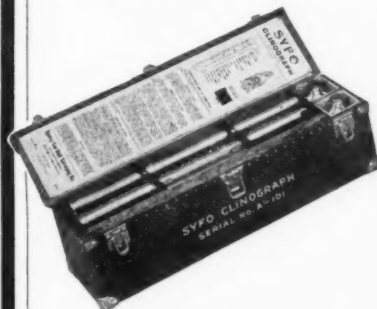
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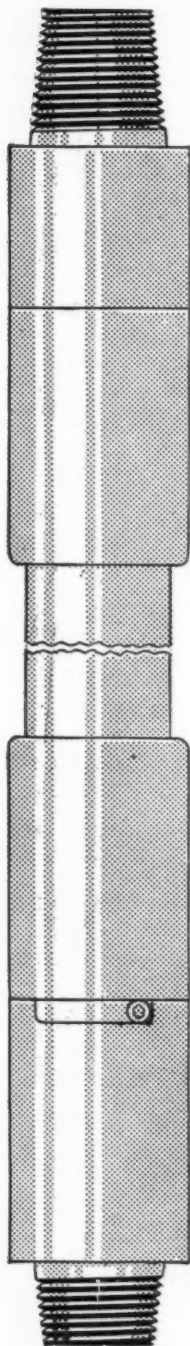
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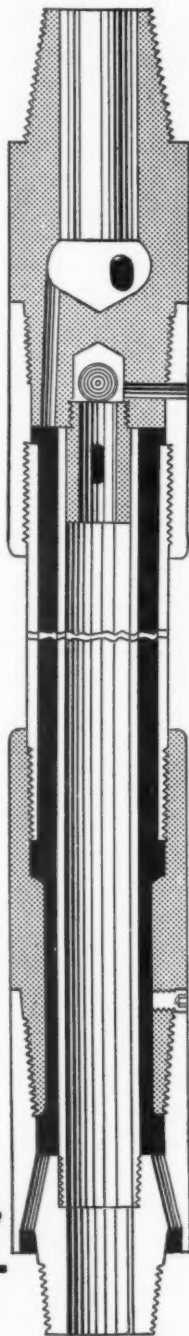
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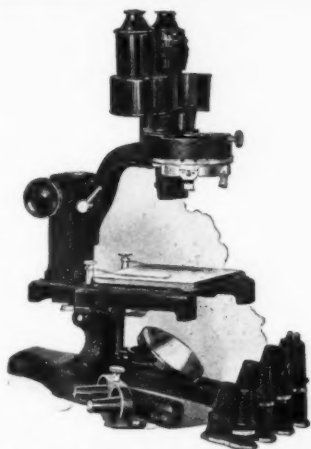
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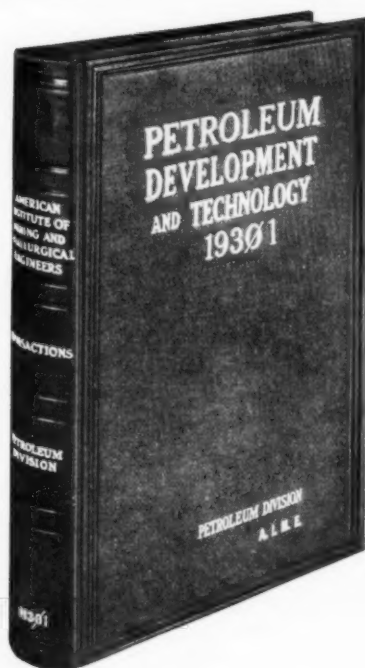
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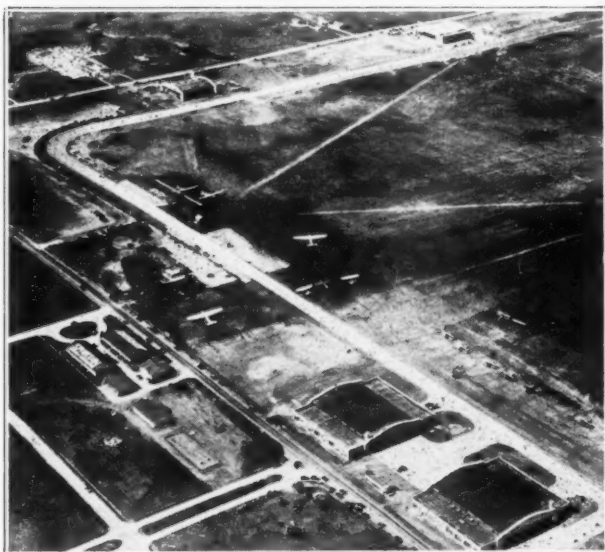
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AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

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Articles Scheduled for Publication in the December *Bulletin*

Utilization of Existing Wells in Seismograph Work

By BURTON McCOLLUM and WILTON W. LaRUE

Analysis of Torsion-Balance Re- sults in California

By ROBERT H. MILLER

Source and Date of Accumulation of Oil in Granite Ridge Pools of Kansas and Oklahoma

By JOHN L. RICH

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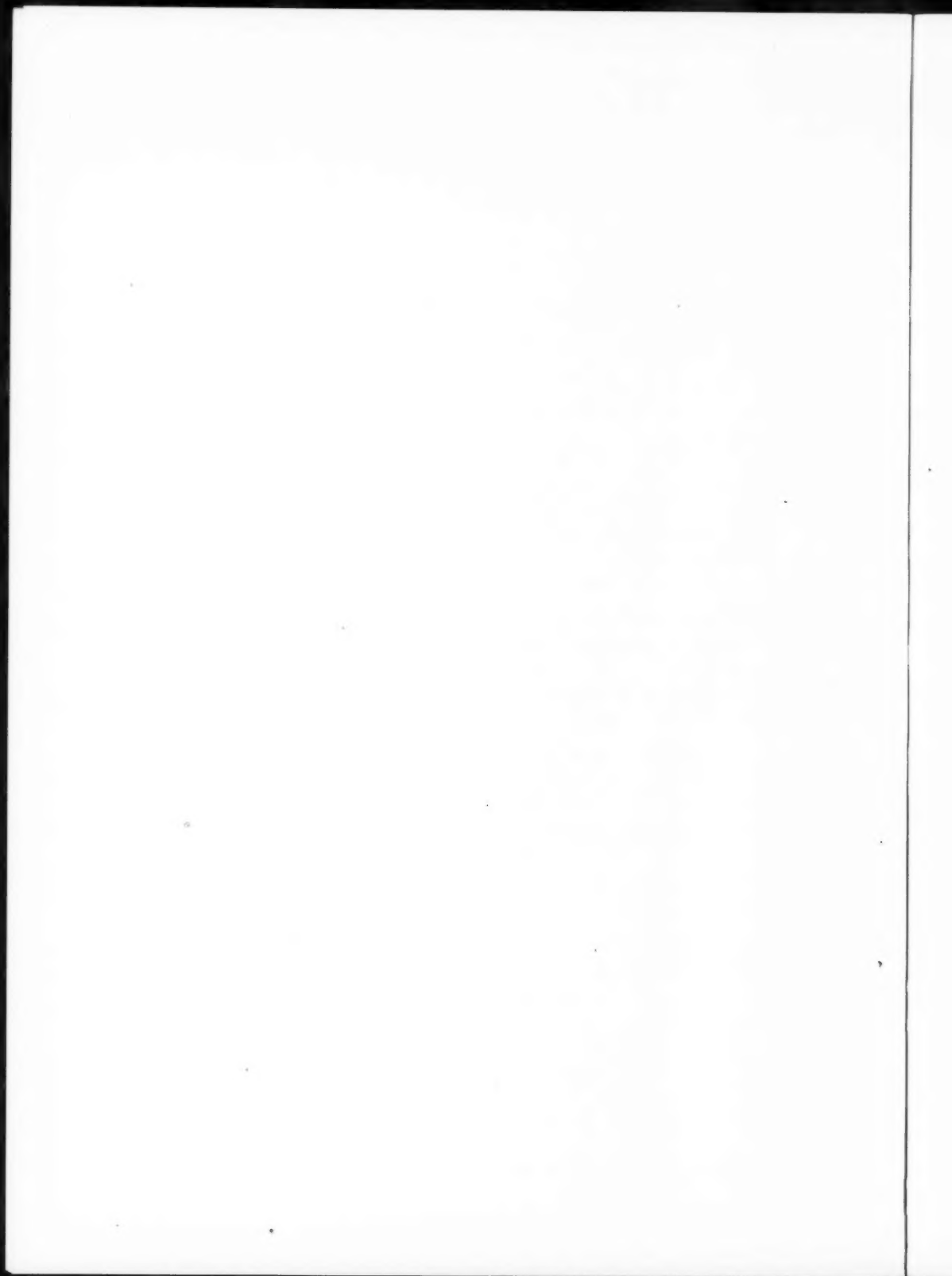
EDITOR'S FOREWORD

In 1929, five major articles on geophysics were published in the *Bulletin*. In 1930, fifteen geophysical papers were printed, including two on geothermal gradients. Eight of these fifteen papers appeared in the September number, but the other seven were distributed through five other monthly issues. This year we have made an effort to concentrate all the strictly geophysical contributions in the November and December numbers.

These papers, which follow, were presented in March, 1931, before the Society of Petroleum Geophysicists at the annual convention of The American Association of Petroleum Geologists at San Antonio. Together with a few others, not now available, they constituted the geophysical group of the Association's technical program. They were solicited largely through the efforts of the program subcommittee, consisting of H. A. Aurand, O. C. Lester, D. M. Collingwood, George M. Bevier, Paul B. Whitney, and G. H. Westby, chairman, all members of both the Society and the Association. To these gentlemen, and especially to Mr. Westby, we wish to express our thanks for their coöperation in making the program a success.

Geophysics is an important tool for helping to decipher the intricate and hidden conditions of the earth's interior. It is an important branch of geological investigation. The real significance of its data can not be satisfactorily interpreted except in the light of geology. We therefore concur with Mr. Westby in his invitation, included in his introduction, for coöperation between geophysicists and geologists; and we wish to add encouragement to the geophysicists to contribute more papers on this important subject.

F. H. LAHEE



INTRODUCTION

During the past year petroleum geophysics in the United States has entered a new, highly important phase of its gradual development and increasingly satisfactory application to the mapping of subsurface geological structure. With the advent of seismic reflection shooting, the locale of most intense geophysical prospecting has shifted from the Texas and Louisiana salt-dome areas to the Mid-Continent states of Oklahoma and Kansas. With this change has come a wider appreciation by geologists and executives of the utility of geophysics. In addition, more geologists now realize that geophysics is not a separate field, but a means of amplifying their ability to determine geological conditions. In short, we have passed from the more or less mysterious isogam and gamma stage to the foot stage in geophysical interpretation.

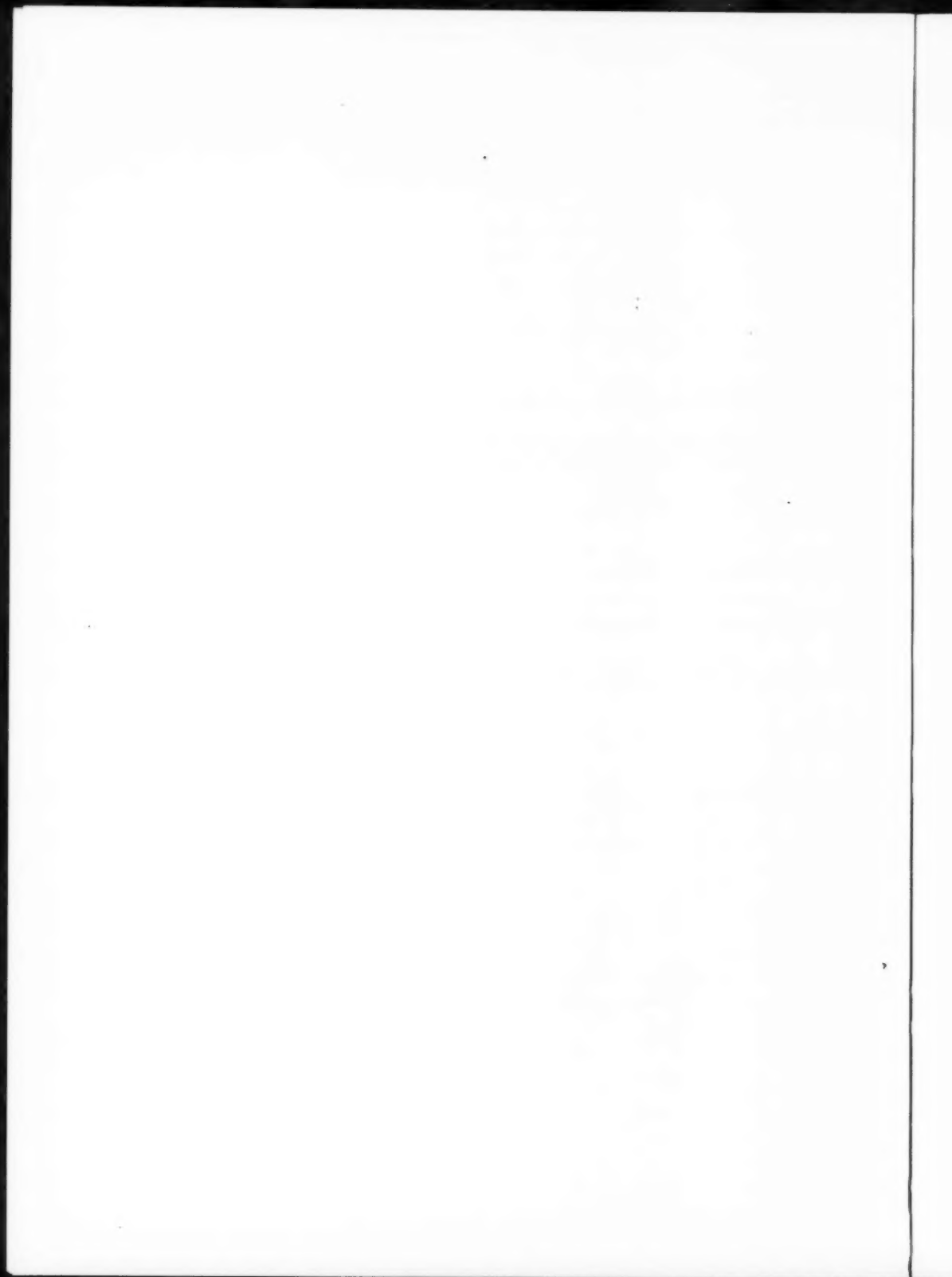
To date it has been difficult to induce most geophysicists to participate in the presentation or discussion of papers. This attitude is a result of the youthfulness of the science. A change may be expected with age. The present period in the science of petroleum geophysics is a recapitulation of the history of geological science in the oil industry prior to the formation of The American Association of Petroleum Geologists. It is to be hoped that the geologists, with their experience in the value of coöperation, will imbue geophysicists with their ideas.

To forward this spirit of coöperation and to acquaint more geologists with geophysical methods, The American Association of Petroleum Geologists, through the Society of Petroleum Geophysicists, solicited geophysical papers to be presented at the San Antonio meeting and later to be published in the *Bulletin*. The following papers, which were presented at San Antonio, represent a fair cross section of the present development of petroleum geophysics. Some of them present new, unorthodox ideas and, though subject to discussion, should stimulate new thought. Such discussion is very necessary, is cordially invited, and if given will accomplish one of the objects in the presentation of these papers.

To the various authors and their respective companies, we are greatly indebted for the release of material and the preparation of the papers.

G. H. WESTBY, *chairman*

San Antonio Program Sub-Committee on Geophysics



APPLICATION OF SEISMOGRAPHY TO GEOLOGICAL PROBLEMS¹

EUGENE McDERMOTT²
Dallas, Texas

ABSTRACT

This paper contains an outline of the principles and methods of applied seismography. The science of seismography is predicated on the elastic properties of earth materials. The refraction and reflection of elastic waves and the conditions governing these are considered. These two phenomena are closely related. The application of the seismic method to salt-dome exploration on the Gulf Coast and the development of the refraction method for general structure determination is followed by an explanation of the reflection method. Several actual reflection records indicate the method of identifying reflections.

INTRODUCTION

The purpose of the writer is to present to the geologist rather than the practicing geophysicist the theory and method of applied seismography. The science of seismography derives its value from the fact that earth materials are elastic and this elasticity has extensive variations. The term seismography as used herein applies to the science which utilizes elastic waves that are generated artificially, as by an explosive charge.

GENERAL THEORY

In general, all materials are elastic, but in varying degrees. By elasticity is meant the resistance a material offers to changing its volume or form when subjected to stress. When stressed a material yields. This yield or change in volume or form is known as a strain. Elasticity may now be defined more accurately as the ratio of this stress to the resulting strain. This strain is propagated through the material with a definite velocity which is a function only of the elasticity and density of the material. This wave of strain is propagated in all directions in a straight line if the material is homogeneous or, more accurately stated, the wave front is spherical. If the material is not homogeneous the path is curved, that is, the wave is gently refracted, and the wave front is no longer

¹Read before the Association at the San Antonio meeting, March 20, 1931. Manuscript received, June 4, 1931.

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spherical. At the contact plane between materials of definitely different physical constants, both refractions and reflections occur simultaneously. Part of the energy in the wave is transmitted through the second material in a direction different from its course in the first material, at the same time that some of the energy in the wave is thrown back as a reflection.

A very instructive illustration of these phenomena is given in Figure 1. In the upper part of the figure a rope fastened to a wall at *B* is held at the other end in the hand. A quick movement of the hand at *A* starts a wave down the rope. This wave travels at a definite velocity for a

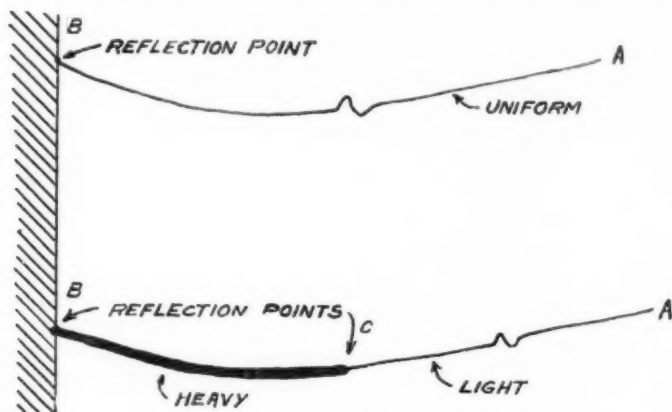


FIG. 1.—Refraction and reflection of wave in elastic rope.

specified weight of rope. On reaching *B*, most of the energy in the wave is reflected back toward *A*. A small part of the energy is refracted and actually causes the wall to move, though very slightly. This illustrates a very efficient reflecting contact between two media.

If, as in the lower part of Figure 1, two ropes of different weights are fastened together at *C*, a somewhat more complicated example of the same phenomena presents itself. In view of this difference in weight, the velocity of a wave is different in the two ropes. A wave travelling down the light rope from its starting point at *A* is partly refracted and partly reflected at the junction of the two ropes, *C*, as well as at *B*. On reaching *C* a reflected wave starts back toward *A* and a refracted wave starts travelling toward *B* in the heavy rope at a slower speed than the original wave travelled in the light rope. On reaching *B* this wave is

mostly reflected as in the previous illustration. *B* is, of course, a much better reflecting point than *C*, because the wall is much more rigid than the rope. It should be borne in mind that at a junction point where refractions and reflections occur, the sum total of the energy in the refracted and reflected waves equals the energy in the original wave. A good reflector point, therefore, means one at which a large part of the arriving energy is reflected back while a small part travels on as a refracted wave.

In the previous illustration we dealt with points of contact between two media. Practically, we are concerned with planes of contact between solid earth materials of different elastic properties. Though this case is obviously more complicated, the same fundamental theory applies. The device of the ropes admirably illustrates the occurrence of reflections, but does not demonstrate the special case of refractions, of greatest value in seismography.

Figure 2 illustrates a simple condition of a soft low-speed and homogeneous earth material overlying a hard high-speed rock which is also homogeneous. The detonation of a charge of explosive at the surface of the ground generates an elastic wave of spherical wave front. What happens to the energy in various parts of this wave front is to be considered. Instead of considering the wave front, it is simpler to use rays which are normal to the wave front. There are, of course, an infinite number of these rays radiating into the earth from the shot point *A*.

As stated previously, the velocity of a wave through any medium depends only on the physical constants of the medium, specifically the elasticity and the density. It is true that the velocity does depend to a certain extent on the coefficient of absorption of the medium, but this is in general of second order in importance and is here neglected. The coefficient of absorption determines the loss of energy in a wave caused by molecular friction.

The velocity of a disturbance may be expressed simply:

$$V = \sqrt{\frac{E}{D}}$$

where *V* is the velocity, *E* is the appropriate coefficient of elasticity, and *D* is the density. In non-rigid media, such as fluids, *E* is simply the incompressibility, whereas in rigid media *E* is a function of both the incompressibility and the rigidity coefficient and may be expressed thus:

$$V = \sqrt{\frac{I + \frac{4}{3}K}{D}}$$

where I is the coefficient of incompressibility, K is the rigidity coefficient, and D has the same meaning as in the first equation.

The foregoing expressions are for longitudinal waves. In longitudinal waves the vibration of the particles is in the direction of wave propagation. Transverse waves also are generated in which the particles of the medium vibrate at right angles to the direction of travel of the disturbance. In all that follows, longitudinal waves only are considered. The velocity of the transverse wave, however, is determined from the following relation:

$$V = \sqrt{\frac{K}{D}}$$

where K is the coefficient of rigidity.

As the speed of propagation depends only on these physical constants of a medium, the longitudinal wave travels in all directions at the same speed in a homogeneous medium. It is obvious that a homogeneous medium must be one which has the same physical constants at all points and in all directions in the medium. By a non-homogeneous medium is meant one in which the physical properties and the velocity of a disturbance vary in different parts of the medium. The earth is such a medium. It is the non-homogeneity of the earth which gives value to the science of seismography. Variations in density are slight compared with variations in elasticity. Hard limestones occur overlain by relatively soft shales. The difference in elasticity of these two materials makes possible definite refractions and reflections. Hard limestones exist in which the velocity is ten times the velocity at the surface. This means that the elasticity of such a limestone must be one hundred times the elasticity of the surface materials, as there is very little difference in density. Even in undifferentiated alluvial sediments the velocity increases with depth as a result of overburdening. Such a gradual change of velocity has no practical value. It is the abrupt changes that are valuable.

Referring again to Figure 2, the simplest example is that of the ray directed vertically downward, AB . On reaching B , some of the energy in the wave is reflected vertically upward while the remaining part generates a wave in the lower medium which travels vertically downward, BC , and, of course, at a greater speed. This is the only example in which the direction of the refracted wave is the same as that of the incident wave.

Now consider a ray travelling obliquely downward, as AF . The refracted ray is bent as shown at FG so that the ratio of sine a to sine c

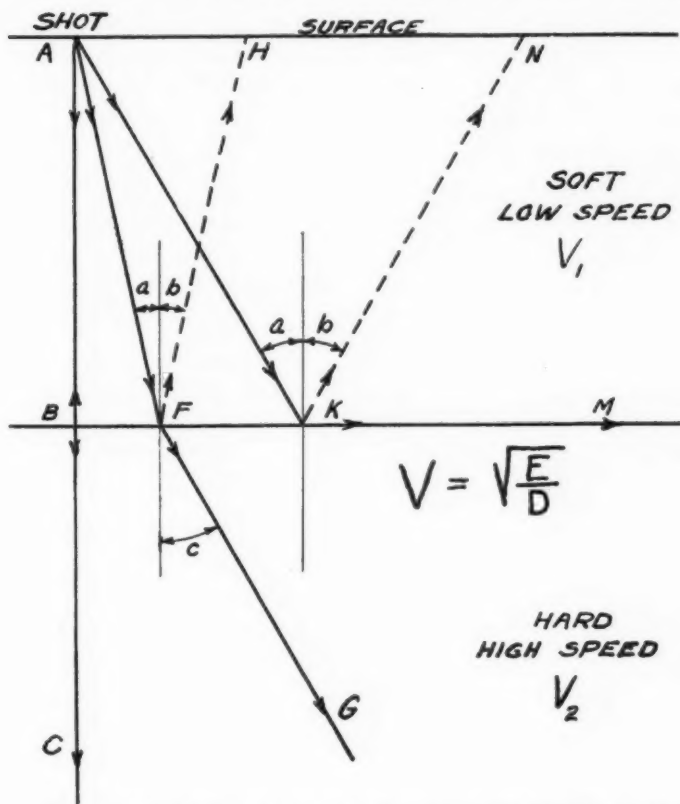


FIG. 2.—Refraction and reflection of waves in passing from low-speed to high-speed medium.

equals the ratio of velocity in the upper medium to velocity in the lower medium. The direction of the reflected ray is such that the angles a and b are equal. Refracted and reflected rays must always obey these two simple fundamental laws, which may be summarized:

$$\frac{\text{Sine } a}{\text{Sine } c} = \frac{V_1}{V_2}$$

$$a = b$$

where V_1 is the velocity in the upper medium and V_2 in the lower. Angle a is known as the angle of incidence, angle b the angle of reflection, and

angle c the angle of refraction. Increasing the angle of incidence finally leads to the limiting case beyond which all the energy is reflected and none is refracted. Such an angle of incidence is known as the critical angle. In this case:

$$\text{Sine } a = \frac{V_1}{V_2}$$

This limiting case is illustrated by the ray AK . The refracted ray KM travels along the contact plane between the two media. This particular refracted ray is the one so much used when using the refraction method for determining structure and is referred to later where that method is discussed.

In actual practice homogeneous strata depicted in Figure 2 are not encountered. There is in all cases an increase of velocity with depth, as a result of which the rays are slightly curved due, of course, to a gradual refraction. In the diagrams, with one exception, this curvature is neglected for the sake of simplicity. No serious inaccuracy can result from this procedure.

REFRACTION METHOD; SALT-DOME EXPLORATION

Seismography found its first practical application in the United States in the field of salt-dome exploration on the Gulf Coast of Texas in 1924. It was a logical and fortunate introduction of a method that was later to extend its usefulness to exploring other types of geologic structure. The first domes sought were very shallow, as deep domes, later discovered, were not at the time known to exist. Naturally those known at the time were only the shallow domes which had given evidence of their presence by surface indications.

The problem was ideal for the seismograph. The relatively large masses of high-speed salt were intruded in uniform and low-speed sedimentary rocks. The velocity in salt may be almost as much as three times the velocity in the rocks which it has displaced. The velocity in salt is 16,000 feet per second, whereas the normal velocity in the surface sediments may be as low as 5,500 feet per second. Time anomalies of $\frac{1}{2}$ second were not exceptional, because of the presence of the salt plug.

In the upper part of Figure 3 the path of the initial impulse arriving at a recording instrument from the shot point is indicated. The curvature of the path is caused, as before mentioned, by the fact that the velocity in the sediments increases gradually with depth. If there is a buried salt dome between the shot and recording points, the first disturbance to reach the recorder is one which has travelled in part through

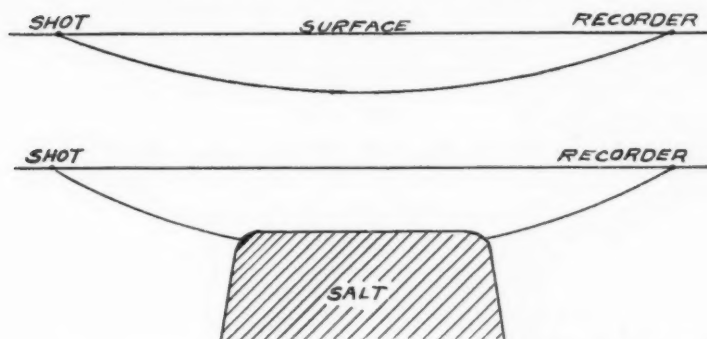


FIG. 3.—Shortest time paths (upper) in sediments and (lower) with salt dome present.

the high-speed salt. For a dome a mile in diameter, which is a fair average, the saving in time is approximately 0.6 second; obviously, the presence of the dome is easily detected.

As the method was applied to progressively deeper domes, the time anomalies to be expected became correspondingly less. It became necessary to increase the accuracy of timing to at least 0.01 second. Whereas the distance between shot and recorder points was previously determined by timing the air wave travelling from shot to recorder, it now became necessary carefully to survey this distance, especially as, for the deeper domes, it was necessary to place the recorder farther away from the shot point. Though a mile or two had been sufficient for the very shallow domes, it was found necessary to use 6-8 miles for the deep domes. This, of course, meant larger charges of dynamite, charges as large as 1,000 pounds being used for a single shot. The large charge required and the increased accuracy necessary in determining the distance between shot and recorder made the work increasingly expensive; also, the smaller time anomalies exhibited by the deeper domes made the results less reliable. However, in a period of 7 years many domes have been discovered by the seismograph.

REFRACTION METHOD; STRUCTURE DETERMINATION

In the study of the comparatively simple problem of searching for salt domes, the attempt was cautiously made to extend the range of usefulness of the seismograph method. Having found a dome, it was desirable to define it in as much detail as possible. It was possible to contour the top of the dome and determine its top edge.

The essentials of this method are illustrated in Figure 4. The refracting layer indicated may be a part of the top of the salt dome. It was mentioned previously that beyond a certain angle of incidence all the energy in an arriving disturbance is thrown back as reflected energy and none is refracted into the second medium. This angle of incidence is known as the critical angle. The ray shown in Figure 4 is assumed to be arriving at the contact of the salt and sediments at this angle. A part of the energy is consequently refracted along the contact surface. Some of this energy returns to the surface and registers on the recorder as shown. If the distance between the shot and recorder points is known and the velocity in the refracting layer is also known, by measuring the time necessary to travel over the path indicated it becomes a very simple problem in geometry to determine the depth to the refracting salt layer. By placing several recorders in a line at known distances from the shot point, called profiling, it is possible to determine the velocity of the refracting stratum. If the layer is not horizontal, it is still possible, by reversing the profile direction, to determine its velocity and at the same time determine the slope. By this procedure the configuration of the top of the salt may be accurately determined. Obviously, the method may be extended to any high-speed stratum other than salt domes. The thicker and more uniform the stratum, the greater the ease with which it may be worked. The method has in fact been extended to the determination of the configuration of several successive strata. The method is particularly adaptable to such regions as West Texas, though less applicable to a region such as Oklahoma.

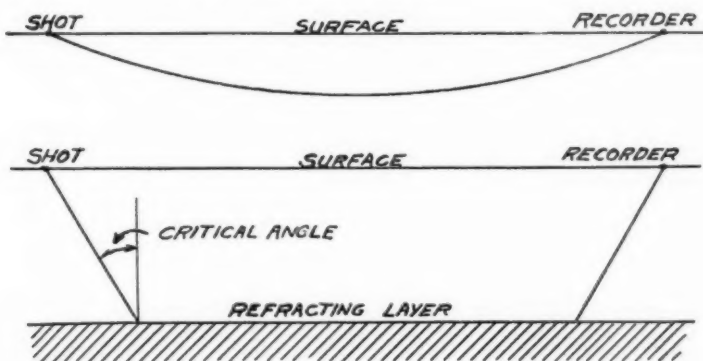


FIG. 4.—Path of wave at critical angle refraction as used to determine structure by refraction method.

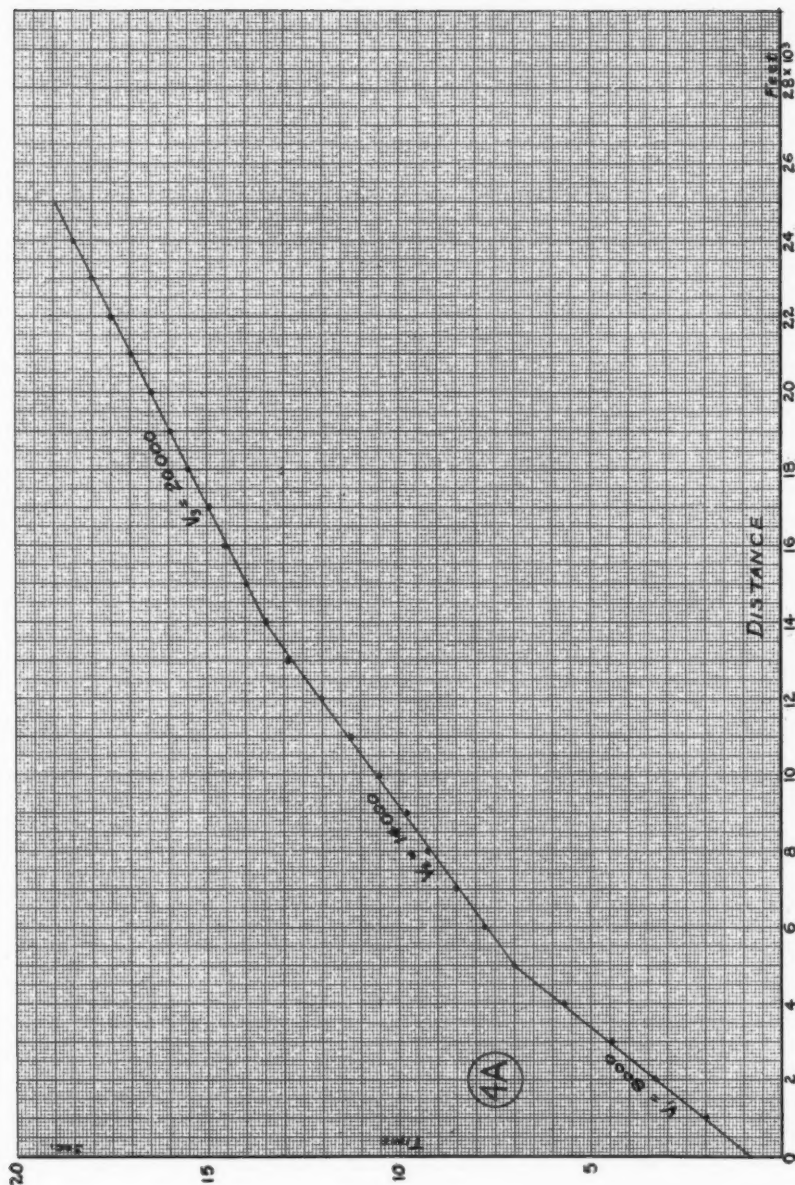


FIG. 4A.—Time-distance curve for movable recorder in Figure 4.

If, in the method of profiling mentioned, the distances from the shot to the recorder points are plotted against the times of arrival for these distances, the graph shown in Figure 4A results. Three lines are shown on this graph. The points falling on the first line are the directly transmitted disturbances, whereas the second and third lines are the result of refractions from each of two high-speed strata. The slopes of these lines represent the velocities in each of the three media.

There is at the surface a thin layer of weathered sediments the velocity of which is very low. It is necessary to determine the thickness of this and the elevations of the shot and recorder points in order to secure the greatest accuracy.

REFLECTIONS

As mentioned previously, refractions and reflections are closely related. One phenomenon rarely occurs without the other. Therefore, it is merely necessary to use the proper instruments and technique in order to separate and make usable the reflected energy that manifestly must be present whenever a disturbance is initiated. Reflections have been identified and have proved more valuable and certainly have permitted greater accuracy than refractions. In the refraction method, only the initial arrival of energy at the recorder was used, because other than initial arrival of energy is more difficult to interpret. The use of reflections, therefore, obviously means a refinement of instruments and method.

In the refraction method the distance between shot and recorder points is several times the depth of the refracting horizon, but in the reflection method this distance is only a fraction of the depth to the reflecting stratum, as shown in Figure 5. Here is shown the path of a reflected disturbance. It should be noticed that the projection of the point of reflection on the surface is midway between the shot and recorder points when the reflecting layer is horizontal. This satisfies the law of reflections that the angle of incidence a must equal the angle of reflection b . By measuring the time between the explosion of the charge and the arrival of the reflected disturbance at the recorder and knowing the average velocity through the medium, the length of the travelled path may be determined. By measuring the distance between the shot and recorder points, the depth may easily be computed as follows:

$$Z = \frac{1}{2} \sqrt{V^2 T^2 - X^2}$$

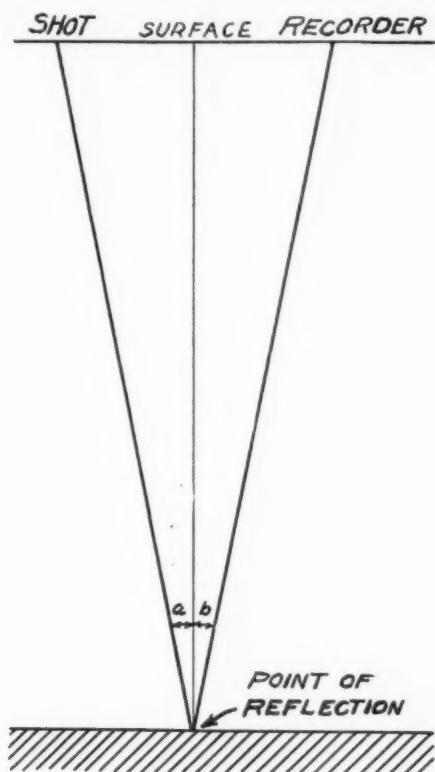


FIG. 5.—Path of reflected wave.

where Z is the depth, V is the average velocity from the surface to the reflecting stratum, T is the time of travel mentioned, and X is the distance between shot and recorder points.

The average velocity through the medium above the reflecting layer is a function of the depth of this layer. As a result, the path of the disturbance is not a straight line as shown in Figure 5, but is curved as shown by the full line in Figure 6. For simplicity the straight path is used in all of the diagrams. The average velocity may be accurately determined by lowering a recording instrument into a well and shooting charges on the surface. A velocity so determined may be used in a large area. As a

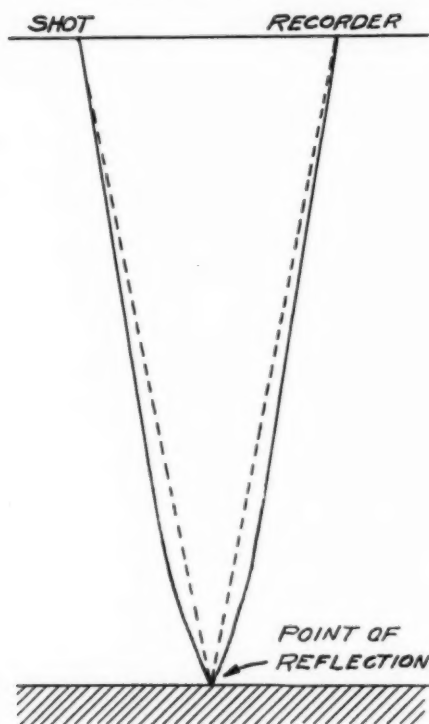


FIG. 6.—Curvature of path due to increasing velocity with depth.

matter of fact, as the accurate determination of relative depths is of greatest importance, it is generally possible to assume an approximate velocity which meets the general requirements of accuracy for absolute depths. Where a well is available, it is possible to check this velocity without lowering a recording instrument into it provided the reflecting strata are not too close together, and the reflections may therefore be definitely identified. In general, in the course of a shooting program, wells are thus checked as they are encountered. An approximate velocity may be determined by arranging several instruments in profile. The foregoing equation of the path of the disturbance is obviously a linear equation between X^2 and T^2 . Thus, if X^2 is plotted against T^2 , the straight line obtained has a slope equal to V^2 . The velocity may thus be deter-

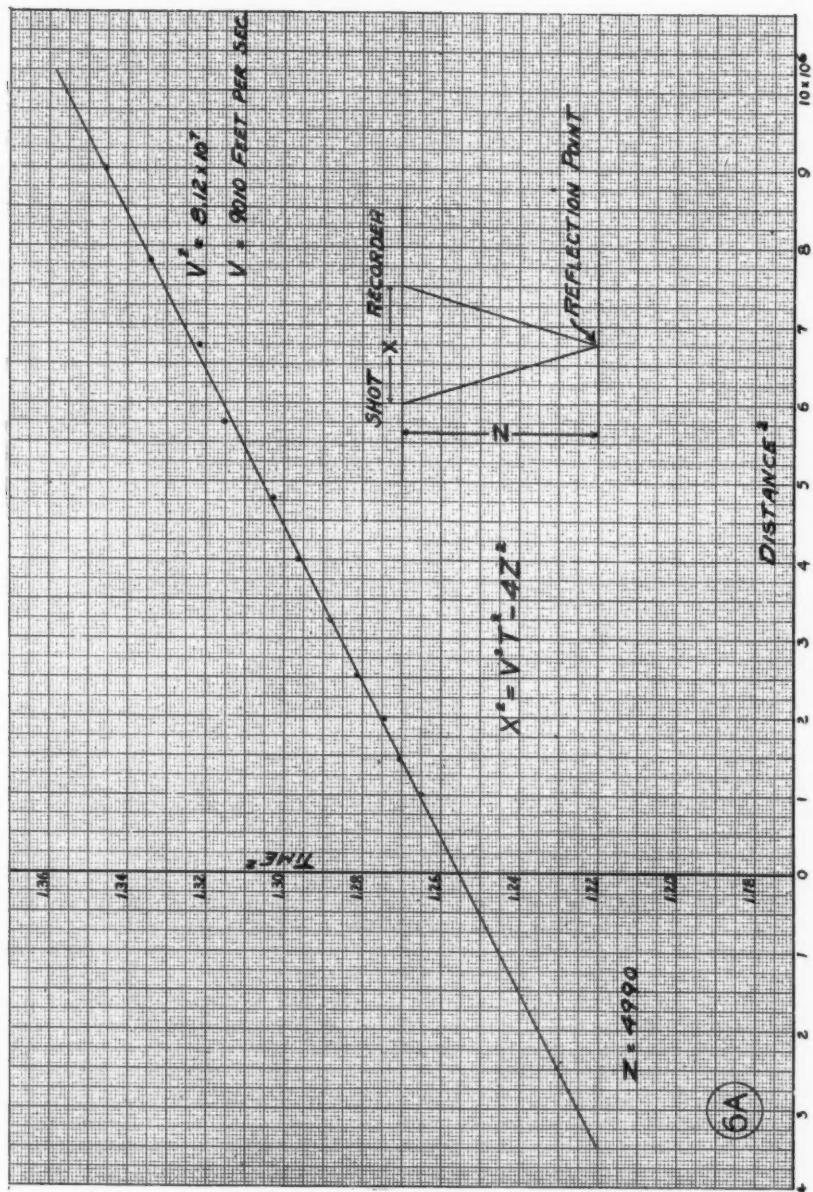


FIG. 6A.—Velocity determination from profile.

mined as shown in Figure 6A. The method is not very accurate, as second order quantities in time are being used. All of these methods, however, combined with experience, permit a fair estimate of the velocity.

The accuracy of the method requires that allowance be made for the thin weathered layer at the surface, as shown exaggerated in Figure 7. A representative thickness for this weathered layer is approximately 30 feet. As the velocity in it is very low—2,000 feet per second as compared with 8,000 in the unweathered layer below it—it can not be averaged with this layer but must be separated, as it varies considerably in thickness. This is accomplished by shooting a small charge at the shot and recorder points. The thickness of this layer and the time consumed in it are thus determined by the refraction obtained from the un-

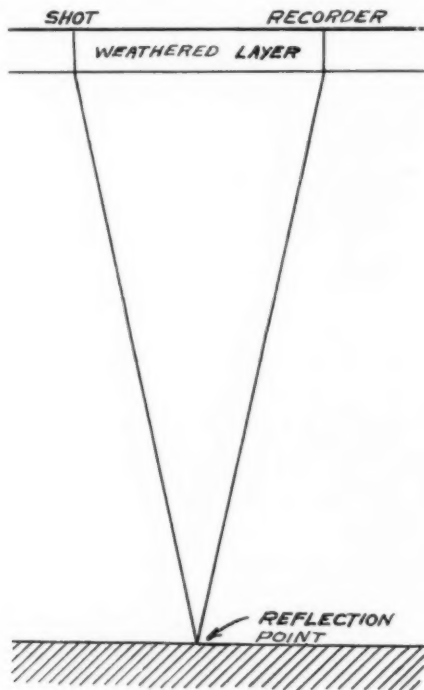


FIG. 7.—Weathered layer (exaggerated).

weathered layer. This is the refraction method applied on a miniature scale. If not accounted for separately in some such manner as this, it may easily introduce an error in depth determination of 100 feet or more. By taking this layer into account and also by determining elevations of shot and recorder points, the general, relative accuracy between two datums obtained by this method is found to be approximately 0.5 per cent. In order to accomplish this, all time measurements must be accurate to 0.001 second. The determination of distance between shot and recorder points need not be very accurate.

In most places several reflecting strata are present in the subsurface, as shown in Figure 8. The recorder responds to each of these reflections as it arrives.

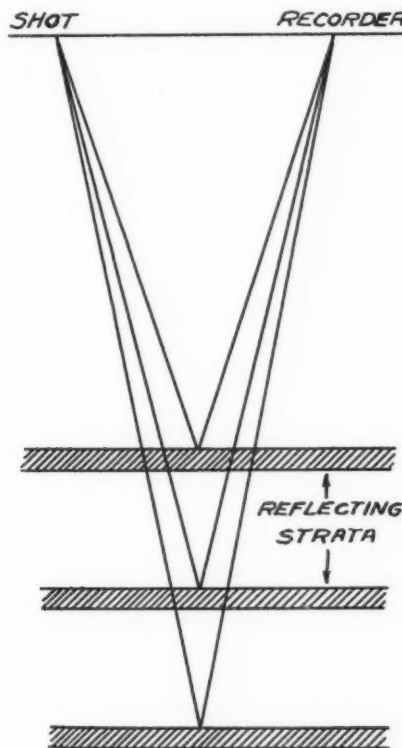


FIG. 8.—Multiple reflections.

The question of identifying reflections naturally arises. The most valuable aid in this identification is the use of several recording instruments, the movements of which are photographed simultaneously on the same strip of paper. These recorders are arranged as shown in Figure 9. The output of each of these recorders is amplified electrically by the desired amount, thus being made to actuate a galvanometer. The motions of the several galvanometers are photographed on the same strip of paper. This strip also has timing lines photographed on it so that the time of arrival of each reflection may be determined. Obviously, in Figure 9 the lengths of the four reflection paths from the shot point to the four recorders are not very different. If the recorders are fairly close to the shot point, the time differences between these paths may not be more than a few thousandths of a second and in general are not more than

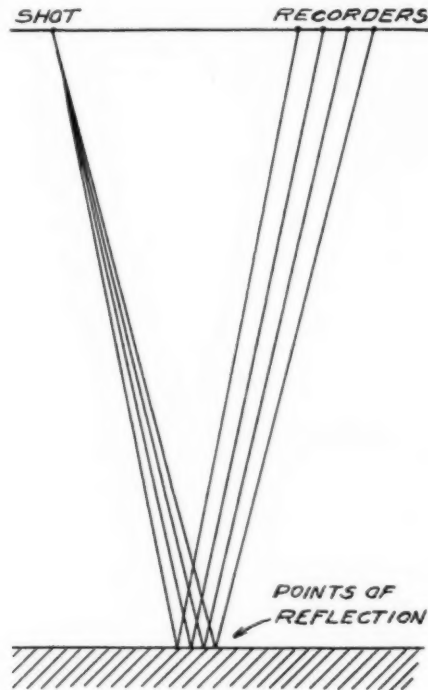


FIG. 9.—Multiple recorders.

0.004 or 0.005. This relation of time of arrival is the principal criterion for the identification of reflections. The differences in arrival time of any other type of wave are considerably greater. For example, the increment of time for the directly transmitted wave is approximately 0.02 second. For refractions from shallow beds to be confused with the reflections would require exorbitantly high velocities in these shallow beds. Beds showing such velocities do not exist.

As a matter of fact there is no great difficulty in identifying reflections on the record. Any difficulties that may present themselves are ordinarily those caused by the presence of too many reflecting strata too close together and the consequent appearance on the record of too many reflections. This, of course, can not be altered without altering the sub-

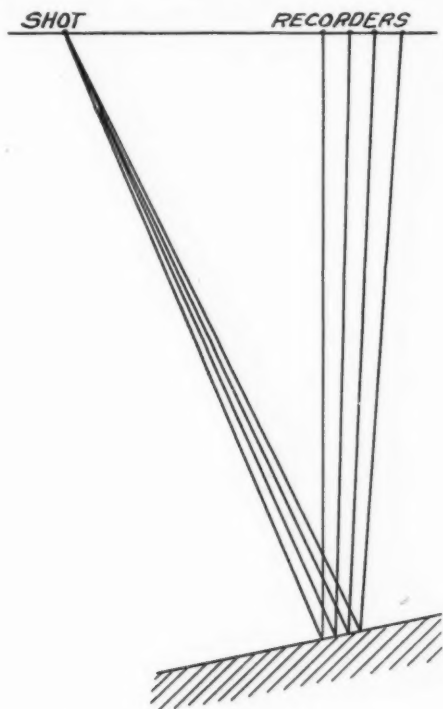


FIG. 10.—Reflections from sloping surface.

surface itself. In general, it is possible to predict the ease or difficulty with which the reflection method may be applied by a study of the geologic column. Well defined hard limestones with shale and sand, especially shale, above them, may be depended on to give good reflections, whereas poorly defined, broken, and siliceous limestones without definite shale breaks may offer difficulties.

Where the reflecting stratum is sloping, as in Figure 10, if the slope is sufficiently great, the reflection may arrive at the recorder farthest from the shot point sooner than at the nearest recorder. Where slopes are sufficiently great, this method may be used to determine slope and, where correlation is difficult, it may be used as an aid to correlation.

Where the presence of a fault is suspected it may be possible to arrange the recorders and shot point so that the fault bears the relation

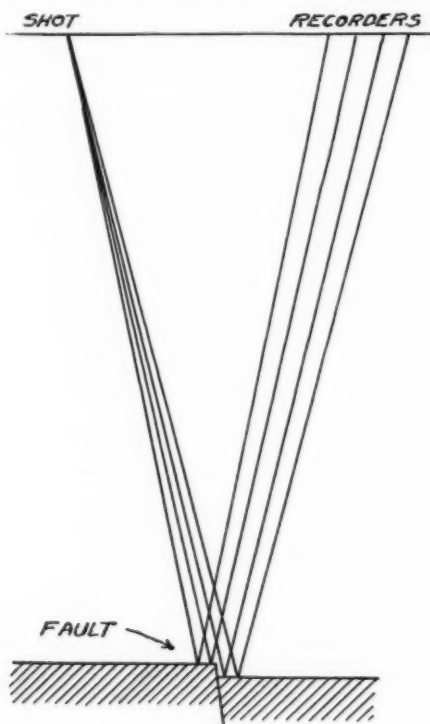


FIG. 11.—Reflections across fault.

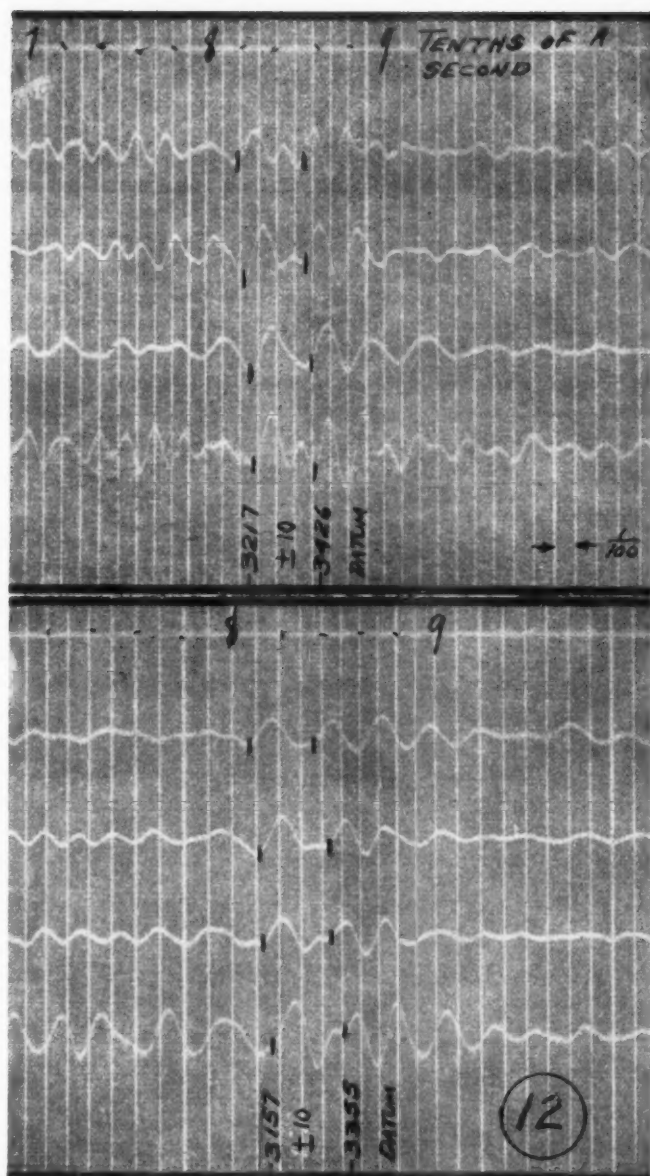


FIG. 12.—Correlation of reflections.

shown in Figure 11. The profile may then be reversed, further to check the fault. As a result of the abrupt change in length of the reflection paths due to the fault, the reflections on the record show a similar abrupt shift.

The average amount of dynamite used to obtain reflections is approximately 3 pounds per shot. In some places the cost of electric blasting caps may actually equal the cost of dynamite, but generally the cost is 50 per cent of the dynamite cost. It may safely be predicted that in the near future the average charge of dynamite for depths of 6,000 feet will not be more than one pound. Even at present the cost of dynamite is only 3 per cent of the total operating costs. As a result of the small charges necessary, damages resulting from the explosion are negligible.

As previously mentioned, the essential problem is that of identifying the reflections from shot point to shot point. In those places where there is but one outstanding reflection, this is a simple matter. Generally, where there is more than one reflecting stratum, the group of reflections has a characteristic appearance, as shown by the group of two reflections obtained from each of two shot points which were located a mile apart (Fig. 12). The vertical lines on these records mark off hundredths of a second and, by interpolating, the arrival of the reflection pulses may be determined to 0.001 second. The four traces are actuated by the four recording instruments already described. Although the frequency indicated in Figure 12 is 50 cycles, this may vary between 15 and 100, depending on the nature of the surface and subsurface rocks and the depth of the reflector.

DISCUSSION

B. B. WEATHERBY, Tulsa, Oklahoma (written discussion received, June 15, 1931): This paper should be of considerable interest to all geologists, but particularly to those of the Mid-Continent area. As a group, Gulf Coast geologists are better acquainted with the method, mainly because it was forced upon them some years ago after most of the surface had been worked for dome indications.

Very little has been published previously concerning reflection work, which is now becoming better known in the Mid-Continent area. As a matter of fact, until recently, many geophysicists denied the existence of reflections. It was natural that after several notable successes the method should come to the front. Inasmuch as the seismograph is a tool by which the geologist can greatly increase his success, particularly when his usual methods are becoming more and more difficult, it behooves him to learn all he can about the comparatively new reflection method.

This article is a good beginning in this direction. As the energy paths in seismology are very similar to those in optics, it is advisable to read also the

chapters on the refraction and reflection of light in any standard physics text book.

Where it can be used, the reflection method has one great advantage over the fan shooting as it was conducted in the Gulf Coast. The older type of coast shooting denoted only the presence or absence of salt domes. Consequently, most of the data obtained were valueless to the geologist. The reflection method, however, gives datum figures on specific beds, and, in conjunction with existing subsurface control, permits the geologist to determine the geology of large areas where, at present, the best that can be done is to interpolate between wells. Consequently, it not only is a great asset in the discovery of petroliferous structures, but it is also increasing geological knowledge to a marked extent.

G. H. WESTBY, Bartlesville, Oklahoma (written discussion received August 20, 1931): During the past year many Mid-Continent geologists were called on to re-examine their determinations of formation datums in wells to permit a closer correlation with seismic reflection data. Errors were found in some determinations or crooked holes were suspected. Most of the seismic-geologic correlations could not be improved. It is probable that some of these men who feel certain of most of their well datums would not agree with Mr. McDermott's statement that generally the relative accuracy between two datums obtained by the seismic method is approximately 0.5 per cent. Despite this disagreement, and fully realizing the possibilities of error in seismic work, most men who have worked with the reflection method feel that it is second only to the use of well samples for the determination of subsurface structure. With this in mind, it seems pertinent to append to Mr. McDermott's excellent paper a short discussion of the present possibilities of error in the reflection method.

Most of the relative errors in the determination of formation datum points by the reflection method are results of the following causes.

- I. Use of erroneous average velocity in calculations
 - II. Errors in the determination of the travel time of reflected or direct impulses
 - III. Insufficient data accurately to correlate reflections from point to point
- I. The use of erroneous average velocity in calculation may be caused by several conditions.

1. Inability to detect and allow for rapid variation in average velocity.

The average velocity to a certain stratum is a function of the stratigraphic section above that stratum. Abrupt lateral variation in character of beds or variation in thickness of limestones affects the velocity. Though variations in velocity from this cause are less than might be expected, it remains as a source of appreciable error.

Seismic Viola datums are in many places affected by changes in the thickness of the Hunton or Mississippian limestone. For example, a change in the thickness of the Hunton limestone from 100 to 300 feet between two seismic stations introduces a relative error of approximately 60 feet in the Viola datums of these points. If the top of the Mississippian or Hunton affords a good reflection, the influence of the thickness of these limestones on the velocity to the Viola can be appreciated and partly eliminated. Where the Mississippian limestone thins over structure, the ordinary effect is to indicate a relief on the

Viola which is less than actual relief. If the changes occur in limestones higher in the section, a more serious problem is ordinarily presented and error occurs which may escape detection.

2. Inability to make corrections locally for gradual changes in average velocity.

From the Seminole area to a point nearly 80 miles north, the average velocity to a depth of 3,500 feet increases approximately 1,000 feet per second. This change is a function of sedimentation and is probably the result of increase in limestone content of the section toward the north. On the assumption that this change is uniform, the use of one velocity chart for calculation of depth points in an area four townships long north and south results in contouring on an inclined plane and the relative error between points on the north and south sides of the area is approximately 150 feet.

3. Inability to construct a velocity depth curve which will hold for varying depths to a certain formation on anticlines and in synclines.

This inadequate knowledge of the average velocity gradient presents only a small error unless the relief is great.

4. The use of a varying shot point to detector distance.

The average velocity to a certain depth is a function also of the distance between shot point and detector. This is a result of change of path by refraction. It can be eliminated by using a constant or nearly constant shooting distance.

5. The use of a constant average velocity.

Where the actual structural relief is great, considerable error may be introduced. If a velocity is used which is less than actual, a diminishing in structural relief will result. However, under some conditions, a constant average velocity affords better results than the use of an increase of average velocity with depth.

6. The assumption of a 2,000-foot velocity for the weathered zone and an 8,000-foot velocity for the unweathered.

These are approximations which may be locally in error.

To evaluate properly the foregoing possibilities of error, it must be noticed that only possibilities 1 and 6 might cause a false determination of the high point of structure. The other possibilities would distort the shape of a structure and give a false impression of the magnitude of the regional structure.

II. Error in the determination of the travel time of reflected or direct impulses may be caused by the following.

Seconds

1. Inability to read records more closely than—	
a. Error in reading weathering record time break	± 0.001
b. Error in reading weathering shot arrival time	± 0.002
c. Error in reading time break of reflection record	± 0.001
d. Error in selecting and reading time of reflected impulse	± 0.001
Total	± 0.005

To this figure may be added ± 0.003 which from experience is the probable error in the weathering correction method. However, as the probable error of

the result is equal to the square root of the sum of the squares of the individual errors, the probable error from these causes is $\pm .004$ sec. or $\pm 25'$ at 5,000 feet.

2. Inability to determine the same point on reflected impulse from record to record.

It is to be noticed that the selection of arrival time of the reflections as shown in figure 12 is not the moment of first arrival of the reflected impulse, but a point somewhat later. It is difficult to select this same point on the reflected impulse in every record. An error of a full period, or about 120 feet in depth, is most frequently made, but ordinarily can be detected in contouring. An error of a half period, or about 60 feet, may pass unnoticed.

3. Variation from true time of point selected for arrival of a reflected impulse when interference with the preceding impulse occurs.

In the lower illustration of Figure 12, the second impulse on each trace interferes with the preceding impulse and the reflection is selected at the interference pattern. The position of this point may vary depending on the ratio of the amplitude of the preceding impulse to the incoming impulse. Theoretically this point may vary 0.005 second from the true time. This is partly an instrumental characteristic and may change with different seismic equipment.

4. Discrepancy between time signal of explosion and actual explosion of dynamite.

This may be the result of defective blasting caps or blasting equipment and can be easily eliminated. However, such errors may exist for some time before being detected.

5. Errors in time-measuring device of seismic equipment.

Because of the present excellence of most of the timing instruments this error is now negligible. Formerly it was a serious and abstruse error.

In summary, each of the foregoing possibilities of error might give a false position for the crest of a structure.

III. Insufficient data accurately to correlate reflections from point to point.

A reflected wave shows on the seismic record as an impulse. In appearance on the record there is nothing to distinguish an impulse received from the Checkerboard limestone from an impulse received from the Dewey limestone. If two reflecting horizons occur close together, as shown in Figure 12, this "character" of impulse is retained as long as the upper limestone and the intervening shale remain constant in thickness. If either of these changes appreciably the "character" changes. "Character" correlation by itself, therefore, may be misleading.

Reflections are ordinarily obtained from limestones in excess of 30 feet which are overlain by shale. It is customary to obtain several reflections on each record and to correlate these groups of reflections from one position to another by means of the intervals. It happens, for no reason known at present, that a reflection which is strong on one record may fail to appear on the next. The correlation of these seismic logs is similar to the correlation of well logs on which some lime tops only were indicated with driller's log accuracy. It is a difficult task where intervals vary within short distances. Where several reflections occur close together, errors in correlations may be made if all reflections do not occur on every record. It is impossible to indicate what error might be

possible from mistakes in correlation, but it is necessary in evaluating a seismic structure to realize such possibilities.

The percentage of relative error is here understood as the ratio of the absolute error in determining the difference in datum between two points to the mean depth of the two points. This is obviously a function also of the distance between the two points, since lateral velocity variation is a function of distance. With this qualification, it is true that, in a small area with many wells where seismic depth points are close together, the relative error may be only 0.5 per cent. However, with the usual mile control in an area with few wells, the relative error is probably of the order of 1 to 1.5 per cent for the better points. It is of indeterminate amount where reflections are poor and correlations questionable.

Despite the foregoing possibilities of error, it must be reiterated that most men who have followed the results of seismic work during the past year are convinced of its great value. There is reason to expect improvements in equipment and technique which will increase the present efficiency.

In order to obtain knowledge of the velocity variations throughout the Mid-Continent region so that correct geologic seismic correlation can be made, it is suggested that seismic data at drilled wells be exchanged by companies engaged in reflection shooting. This type of coöperation would be similar to an exchange of well samples.

PAUL WEAVER, Houston, Texas (written discussion received, August 21, 1931): Mr. McDermott calls attention to the importance of determination of the thickness of the "weathered layer" in accurate reflection work. In many places the thickness of this layer is greater than that which the geologist calls the "zone of weathering," and pending a more thorough analysis of the problem of the low velocity of seismic waves near the surface, it seems advisable to use the expression suggested by McCollum, "surface correction zone," because for it a "surface correction" is applied to the travel time. This zone has a low velocity, even in areas where diluvium, alluvium, et cetera, are thin or absent, such velocity extending much deeper than the deepest level of the ground water. The velocity is much lower than that of the beds immediately below, even when the geologist fails to detect a change.

It is suggested that, as overlying beds are removed by erosion, the lower beds thus released from pressure may manifest an "elastic rebound," and cause a change in density, which manifests itself in a greater porosity near the surface than in the same lower beds where under greater cover.

I hope that seismologists will measure the thickness of this "surface correction zone," and compare the number of feet thus obtained with the number determined for the depth to lowest ground water, that is, the zone of weathering which the geologists consider.

BELLE ISLE TORSION-BALANCE SURVEY, ST. MARY
PARISH, LOUISIANA¹

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ABSTRACT

The geological prediction was made that the Belle Isle salt dome might be much larger than supposed. The torsion balance was used to corroborate that prediction. From the data of the torsion-balance survey, calculations were made of the probable depth, thickness, and edge of the cap rock. Seven sulphur tests were drilled on locations made on the basis of the calculated conformation of the cap. The predictions in regard to depth were shown to be 73 per cent correct, and in regard to the thickness of the cap, 58 per cent correct. The causes of the errors were probably the unfavorable marshy terrane, the assumption of a slightly too small relative density for the cap rock, and the irregularity of the conformation of the dome.

INTRODUCTION

This paper records an actual ordinary torsion-balance survey and the degree of success which was obtained in an attempt to base quantitative predictions on the torsion-balance data. The choice of this survey for publication was not made on the basis of exact verification by subsequent drilling. The accuracy of the predictions may seem somewhat disappointingly poor, if the actual cap rock which was encountered in the subsequent test well is compared with the predicted cap rock (Fig. 3). The survey, however, accomplished successfully the qualitative and semi-quantitative tasks assigned to it. This survey is more or less representative of the degree of success attained by the average successful geophysical surveys, although it was made under adverse terrane conditions; most of the stations were on unstable marsh, and a lake precluded stations in a wide central area.

The cap rock as a whole is thinner, deeper, and steeper than was predicted and the inner part of the cap was very much thinner than was shown in the calculated west-east and southwest-northeast sections. These errors are in part caused by two factors: the absence of stations in

¹Read before the Association at the San Antonio meeting, March 21, 1931. Manuscript received, March 20, 1931. Data released for publication through the courtesy of the Freeport Sulphur Company and Belle Oil Corporation.

²Consulting geologist and geophysicist.

South Pond, and the fact that, mathematically, a limited series of bodies may produce the same gradient profile, particularly if the probable error of observation at each station is moderately large and if, as at Belle Isle, the available gradient profile does not sufficiently cover the anomaly.

Location.—Belle Isle salt dome is in T. 17-18 S., R. 10 E., in St. Mary Parish, Louisiana, 15 miles south-southwest of Morgan City. Belle Isle properly is a triangular island of dry land which rises out of the flat low marshes to a maximum elevation of 80 feet. It lies in the sea marsh at the shore of Atchafalaya Bay. South Pond (Belle Isle Lake) marks the center of the dome.

History.—The exploration of Belle Isle began in 1896 when Captain Lucas drilled his well on the west edge of the island. The presence of the salt was disclosed by Lucas' second well, which was drilled in 1897 in the northern part of the island. After a series of wells were drilled to outline the salt, two unsuccessful attempts were made to sink shafts into the salt and to mine the salt.

Several tests were drilled for oil in the period 1906-1916.

Six sulphur tests were drilled during 1916-17 under the direction of Captain Lucas. In 1921, the Union Sulphur Company drilled more sulphur tests on the dome and oil tests on the north and east flank.

The top of the cap-salt core of a salt dome had been shown by the drilling prior to 1929 to be coincident with the island of Belle Isle (Fig. 1). That drilling had been confined to the area of the island and to the edge of the marsh on the east side and north point of the island. The edge of the dome had been delimited by deep flank wells only on the east and north. The physiography indicated that the northwest edge of the island probably marked the northwest edge of the dome. The position of the south edge of the dome was indefinite. There is a south dip on the top of the salt from the center of the island to Syndicate well No. 5 at the head of South Pond and the assumption was made by many geologists that the south edge of the dome lay in the pond, 1,000-1,500 feet south of that well. The belief was held by some geologists that South Pond reflected the presence of the dome and the south edge of the dome probably lay south of the pond. The salt domes of the Five Islands have a common individuality that is not shared with the other domes of the Gulf Coast. One of the features of that common individuality is a diameter of approximately 2 miles. South Pond is an exceptional lake in the marshes of St. Mary Parish and its position on the indefinitely delimited side of the Belle Isle dome seemed definitely suggestive.

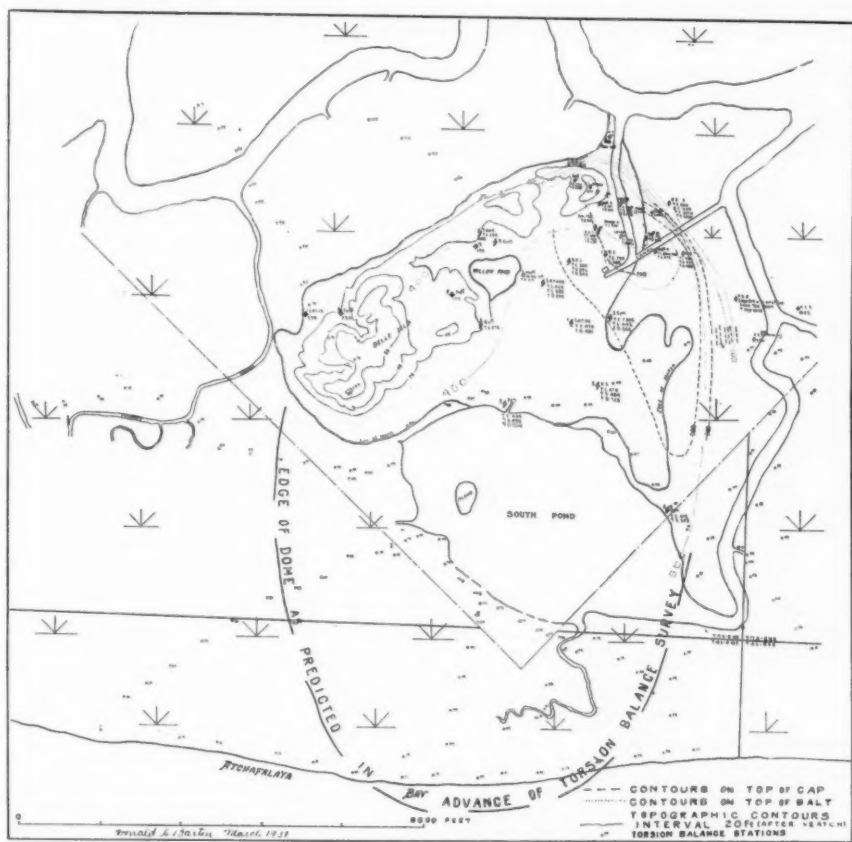


FIG. 1.—Known and predicted conformation of Belle Isle salt dome in advance of torsion-balance survey.

In a report made to the Freeport Sulphur Company in 1928, the writer stated that the dome probably extended under the pond, as far as the shore of Atchafalaya Bay and possibly slightly out under the bay, and that more than half of the probable cap-rock area had not been explored. The company made a torsion-balance survey of the dome and in 1929-30 drilled seven cap-rock tests in the southwest quadrant of the dome. The locations for the tests were made on the basis of the torsion-balance survey.

The results of the Freeport Sulphur Company's tests, as well as of the Union Sulphur Company's tests and of earlier cap-rock tests, condemn the dome as a favorable sulphur prospect, although there probably remains a narrow band of untested cap-rock on the northwest flank of the dome. The top of the dome has been condemned for cap and super-cap oil production. The flank sands are practically untested. Good showings of 37° Bé. gravity oil have been found in the salt—in Knapp No. 1 at 125 feet and from 1,500 to 3,171 feet—and suggest that oil sands may be present in considerable depth.

Geologic situation.—The Belle Isle salt dome rises through an enormously thick stratigraphic section of late Tertiary sediments. Paleontological data are not available for the few moderately deep wells at Belle Isle, but from more recent deep drilling in this general area, it seems probable that the Pleistocene and Pliocene beds together have a thickness of more than 6,000 feet at Belle Isle. The thickness of the Miocene and older formations is not known.

TORSION-BALANCE SURVEY

Tasks.—The tasks which were attempted by use of the torsion balance in the survey of the dome were: (1) to verify or disprove the predictions of the extension of the dome to the shore of Atchafalaya Bay; (2) to determine whether a sufficiently thick cap rock was present at a sufficiently shallow depth and on a sufficiently large area to make the unexplored area a favorable sulphur prospect, and (3) to determine the edge of the cap so that locations could be made for wells for the purpose of exploring the cap near its edge.

Survey.—The field survey was made under the direction of the writer by C. I. McGlothlin, torsion-balance observer of the Freeport Sulphur Company, during the winter of 1928-29. Two large Süss (visual) torsion balances were used. Observations in general were made only during the day time; the observation at each station was continued until five successive good readings had been taken.

Most of the terrane was poor. Except for a few stations on the dry land of the island, the stations were on the sea marsh, which in general is covered with coarse, hummocky grass. The marsh is so soft that an 11-foot length of 2-inch pipe can be pushed into the marsh, level with the surface, by two men and pulled up by three men. Each foot of the instrument tripod was placed on the top of such an 11-foot length pushed down flush with the surface of the marsh. The instrument house was placed directly on the marsh. At times the foot of the instrument was under water. It was impracticable to clear off and level the station site; and on account of the grass hummocks and the soft character of the muddy ground between hummocks, the conclusion was reached that less error would be introduced by neglecting the terrane correction of the marsh stations than by taking levels and calculating the correction.

The instruments and shelter houses were carried by hand. On account of the difficulty of movement across the marsh and the many readings which had to be taken at each station, only one station per day per instrument could be obtained in the marsh.

A long east-west line of stations on the beach, and eight radial lines of stations were occupied. An average station interval of 400 feet was used. Although stations in South Pond would have been desirable, no attempt was made to occupy them because of the difficulties in occupying stations in the water.

Results of survey.—The results of the field survey are shown in Figure 2. The results of the preliminary line of stations which were occupied along the beach showed that the dome extends south of South Pond but does not reach the beach, that probably considerable cap rock might be expected on the south end of the dome, and that it would be advantageous for the Freeport Sulphur Company to make a detailed torsion-balance survey of the dome.

The results of the west, southwest, south, and southeast radial lines of stations showed that the Belle Isle salt dome is elliptical in plan, that its major axis has a north-northeast strike and a length of approximately 2 miles, and that much cap rock might be expected in a broad area south, southwest, and west of South Pond, probably at moderate depth. The approximate position of the edge of the dome is delineated in the gradient arrow map (Fig. 2) by the zone of maximum gradient which from tangency to the east side of the island swings clockwise across the outlet to South Pond, then southwest and west of South Pond to tangency to the northwest edge of the island.

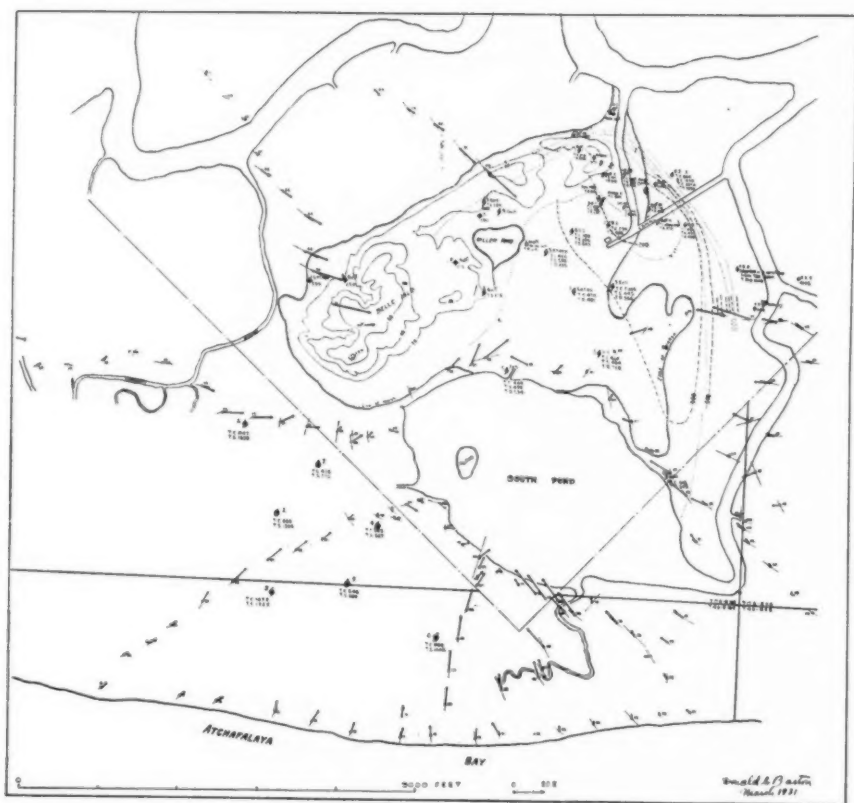


FIG. 2.—Gradient arrow map of Belle Isle salt dome.

The results of the field survey with the torsion balance, therefore, qualitatively verified the prediction of a large unexplored area of cap rock. The next task was to make a quantitative calculation of the amount and depth of the cap rock and the position of its edge.

Cap-rock calculations.—The calculation of the amount, depth, and edge of the cap rock was made by a series of trial and error calculations, profile by profile. A trial cross section of the dome along the selected profile was sketched; its gradient profile was calculated and then compared with the observed gradient profile; the trial cross section was remolded or replaced by a new sketch cross section; the gradient profile was calculated and compared with the observed gradient profile; the cycle was continued until a cross section was found whose calculated gradient profile fitted the observed gradient profile more closely than did the gradient profile of any of the other trial cross sections.

The calculations in connection with the torsion-balance survey at Belle Isle were made graphically by means of one of the writer's graphic charts (8).¹ The principle of these charts is that space is divided into rectangular prisms at right angles to the vertical plane of the section; the length of the prisms is calculated so as to vary by some simple law to approximate the dimensions of the structure at right angles to the plane of the section; the cross section of each prism is so calculated that each prism produces a gradient of 1E at the origin; if the cross section of a structure is sketched on transparent paper and superimposed on the chart, it is necessary only to count squares and multiply by the specific gravity in order to obtain the gradient at the origin. The actual calculations in connection with the Belle Isle survey were made by the writer's assistant, Mrs. Elizabeth B. Summers.

The specific gravity relations which were used were those which seemed geologically the most probable on the basis of the laboratory determinations of the specific gravity of cores from the cap rock at Bryan Heights, Hoskins Mound, and other domes and from cores of sediments from depths less than 3,500 feet and on the basis of experience in previous calculations in connection with other domes. Those assumed density relations are given in Table I.

For the purposes of checking, several other sets of assumptions were tried. Two of the more important sets of those assumptions are given in Table II.

¹Numbers in parenthesis refer to list of references at end of article.

TABLE I
GEOLOGICALLY MOST PROBABLE SPECIFIC GRAVITY RELATIONS AT BELLE ISLE

Depth in Feet	Specific Gravity			Relative Density	
	Sediments	Cap	Salt	Cap	Salt
0- 300	1.00		2.20		+0.30
300- 700	2.00	2.60	2.20	+0.6	+0.20
700-1,200	2.10	2.70	2.20	+0.6	+0.10
1,200-1,600	2.15	2.75	2.20	+0.6	+0.05
1,600-4,400	2.20	2.80	2.20	+0.6	+0.00
4,400-8,000	2.30		2.20		-0.10

TABLE II
ALTERNATIVE ASSUMPTIONS IN REGARD TO THE SPECIFIC GRAVITY RELATIONS AT BELLE ISLE

Depth in Feet	Specific Gravity						Relative Density					
	Sediments			Cap			Salt			Cap		
	A	B		A	B		A	B		A	B	
300- 600	2.00	1.95	2.60	2.55	2.30	2.25	+0.6	+0.6	+0.6	+0.30	+0.30	+0.20
600-1,000	2.10	2.05	2.70	2.65	2.35	2.30	+0.6	+0.6	+0.6	+0.23	+0.25	+0.10
1,000-1,600	2.15	2.10	2.75	2.70	2.35	2.30	+0.6	+0.6	+0.6	+0.20	+0.20	+0.06
1,600-3,000	2.20	2.15	2.80	2.75	2.30	2.25	+0.6	+0.6	+0.6	+0.10	+0.10	0.00
3,000	2.25	2.20			2.30	2.25				+0.05	+0.05	-0.03

The assumptions (*A* and *B*) of Table II gave a very much better agreement of the calculated with the observed gradient profiles than did the geologically more probable assumptions of Table I. The assumptions of Table II evolved more or less mathematically in the process of the calculations. Geological analyses of these assumptions showed that geologically they were possible but somewhat improbable. Assumption *A* makes the specific gravity of the sediments slightly lower than seems probable and necessitates a content of approximately 15 per cent of anhydrite in the salt. Assumption *B* uses the geologically most probable densities for the sediments but uses a density for the salt which connotes an average anhydrite content of approximately 24 per cent. But the average anhydrite content of the salt in the near-by Weeks and Avery Island salt mines is approximately 1 per cent, and in the two analyses of Belle Isle salt which are available, the percentage of NaCl in the one analysis is 92.8 and in the other, 96.4. The density used for the salt in Table I connotes an anhydrite content of 7 per cent. An average anhydrite content of considerably more than 7 per cent in the salt theoretically is not impossible, but has not been encountered in the shaft or the wells into the shale. The assumptions of Table II, therefore, were discarded on account of their geologic improbability and the geologically most probable assumptions of Table I were used, although mathematically they did not give as good results as did those discarded assumptions.

The known data in regard to the depth of the top of the cap and of the salt were utilized and before the calculations were made for profiles in the unexplored areas, sections were calculated through the areas in which the conformation of the salt and cap were best known.

The calculated structural sections for the profiles in the southwest quadrant are shown in Figure 3. Each structural section is the final choice out of a long series of sections calculated for that particular profile. If the structural sections which were calculated with the discarded density assumptions of Table II had been retained, the predictions regarding the position of the edge of the cap and depth to the top of the cap would have been the same, but the thickness of the cap would have been predicted as approximately 100 feet.

The calculated structure contours on the top of the cap, or, in the absence of the cap, on the salt, are shown in Figure 4. The structure contours were made to conform to the known data from the drilling in the northeast quadrant.

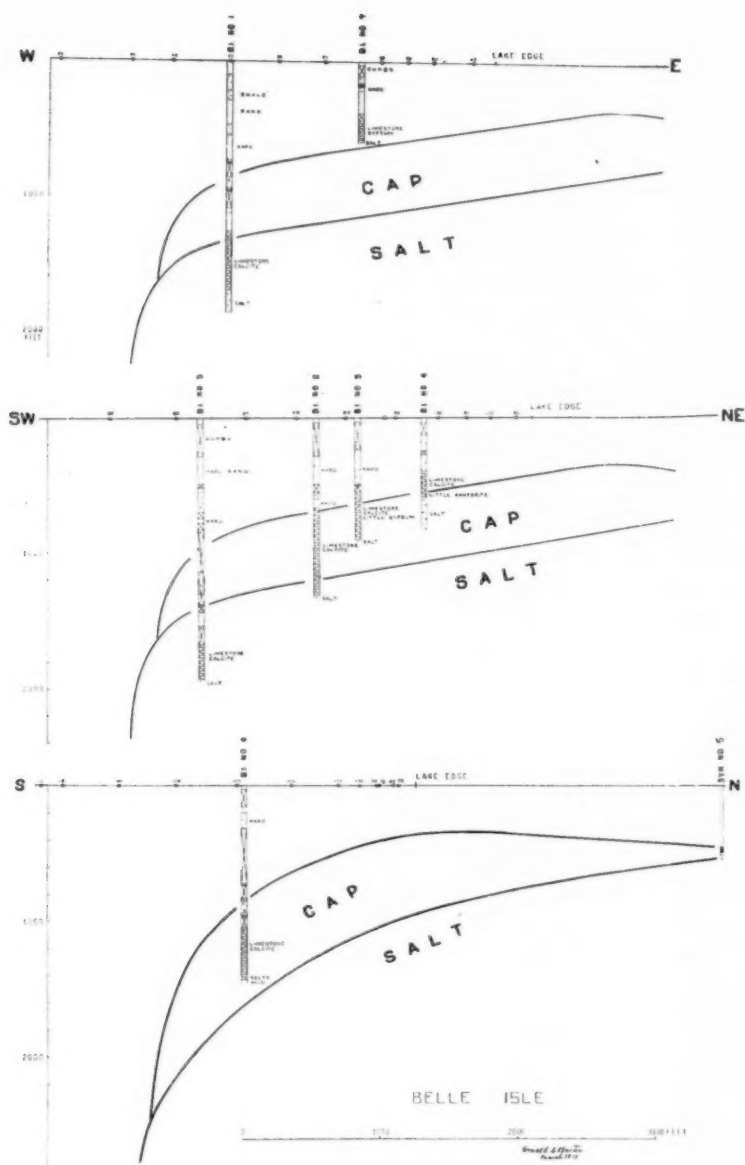


FIG. 3.—Calculated cross sections of southwest quadrant of Belle Isle salt dome and graphic logs of subsequent sulphur tests.

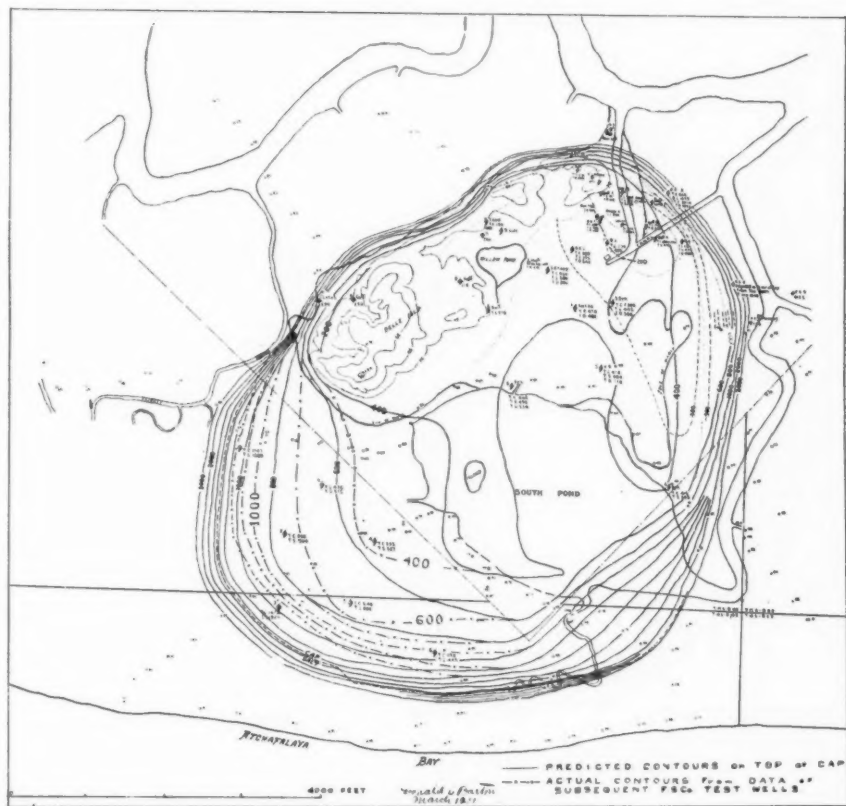


FIG. 4.—Structure contours on top of cap as predicted from calculations versus structure contours determined by results of drilling.

The following additional verbal predictions were made.

Over South Pond the top of the cap seems to lie at a level of about 400 feet below the surface. There seems to be a moderate amount of cap present, of the order of 100 to 300 feet in thickness, but on account of the absence of stations in the lake, our estimates of the thickness are only very crude.

In the southwest quadrant, west and southwest of South Pond, a moderately thick cap rock seems to slope gently west and southwestward. The thickness of the cap, according to our estimates, is of the order of 500 feet. The actual thickness may be less or greater. There are slightly greater possibilities for the actual thickness to be somewhat less than for it to be greater. . . .

The odds that the cap is appreciably thinner than on the sections but still of very considerable thickness are 35 out of 100.

The accuracy of the observations on which we had to base our calculations is fair, but is not as good as it was at Hoskins Mound or Bryan Heights. Practically all the stations were taken on the marsh where it is impossible to get good station sites or to make first-class observations. The terrane is so soft and unstable that it is practically impossible to get readings which will check as well as we would like. . . . Slight indefiniteness in our knowledge of the actual gradient at each station throws a corresponding indefiniteness into the results of our calculations.

The accuracy of the calculations is less for the relations of the salt than for the cap and the accuracy for either decreases rapidly with increase of depth below 1,500 feet.

VERIFICATION

Seven wells were drilled by the Freeport Sulphur Company in the previously wholly unexplored area of the southwest quadrant. The location of each test was based on the calculated structure contours of Figure 4 and the calculated cross sections of Figure 3.

The verification of the calculated predictions in regard to the cap rock qualitatively was good, although quantitatively there was an average error of 27 per cent in the predicted depth and of 42 per cent in the predicted thickness of the cap (Table III). The partial graphic well logs plotted in the profiles of Figure 3 and the dashed structure contours in the southwest quadrant of the dome in Figure 4 show graphically the degree of verification.

The errors, in the main, are two: that the actual thickness of the cap is only two-thirds the predicted thickness and that the actual depths to the top of the cap were greater than the predicted depths on two profiles and less on the intervening profile.

The calculated predictions, in spite of their error of 27-40 per cent, accomplished the purposes for which they were made. The cap was present in substantially the amount and position which were predicted and the predictions were sufficiently accurate to permit tests to be located in advance of exploration.

TABLE III
VERIFICATION OF PREDICTED DEPTH AND THICKNESS OF THE CAP ROCK
(Wells of Freeport Sulphur Company)

Well Number	Depth to Top of Cap in Feet			Thickness of Cap in Feet			Total Depth	Character of Cap Rock
	Predicted	Actual	Error	Predicted	Actual	Error		
1	850	1,247	-397	470	442	+ 28	1,853	Hard lime rock with calcite veins, mostly impervious
2	600	660	+ 30	510	644	-134	1,321	Same as foregoing
3	1,180	1,672	-492	410	253	+157	1,040	Same as foregoing
4	550	393	+157	470	174	+296	828	Limestone and some gypsum and anhydrite
5	650	546	+104	500	327	+173	880	Same as foregoing
6	860	1,058	-198	740	387	+353	1,445	Broken lime rock and calcite; voids filled with sandy shale
7	620	426	+194	730	140	+581	580	Broken lime rock, calcite and gypsum; voids filled with sandy shale

Percentage errors in predicted depth to the top of the cap:

46, 4, 41, 28, 16, 23, 31

Numerical mean, 27 per cent

Percentage error in predicted thickness of the cap:

6, 26, 38, 63, 34, 47, 79

Numerical mean, 42 per cent

CAUSES OF ERRORS

The errors in the calculated predictions probably arise from a series of causes.

The unfavorable conditions under which the observations were made are sufficient to account for considerable error in the magnitude of the observed gradient values. Because of the marsh terrane, it was impracticable to maintain our normally rigorous limits of error in the readings. The impracticability of taking the terrane levels and of making the terrane corrections probably led to the introduction of some error into the observations. An error of even 1 E with the same sign at three consecutive stations critically placed at the edge of the dome easily might cause considerable errors in the calculated position of the cap and in the calculated depth to the top of the cap on the flank. The error shown by well No. 1 on the west radius could be caused by an error of +2 E in the observed values of the gradient in the two stations above the predicted edge of the cap on that west radius. Errors in the observations at those stations are especially probable as the stations are near a bayou.

The error in the predicted thickness of the cap probably indicates that the assumed relative density is too small. The relation holds very roughly that if the relative density times the reciprocal of the area of cross section of a very long horizontal body is a constant, the gradient is constant. If, in the present calculations of the Belle Isle survey, too small a relative density were used for the cap rock, the predicted thickness of the cap would be too great. The cap proved on the whole to be tight and to have little of the porosity commonly present in the lime rock of the cap. The assumed specific gravity of the sediments also may have been slightly too high and actual specific gravity of the sediments may be 1.9 to a depth of 700 feet and 2.0 from 700 to 1,200 feet instead of 1.9 from the surface to 300 feet, 2.00 from 300 to 700 feet, and 2.1 from 700 to 1,200 feet, and the relative density might be 0.8 instead of 0.6. A difference between an actual relative density of 0.8 and the assumed relative density of 0.6 would be sufficient, substantially, to have caused the error in the prediction of the thickness of the cap.

Irregularities of mass at right angles to the plane of the section can not be detected by this type of calculation. The gradient profile is essentially the same, whether the mass is concentrated in the vertical plane of the section, or a slightly greater mass is uniformly and symmetrically disposed at right angles, or a certain mass is symmetrically concentrated at two points on opposite sides of the plane of the section. The upper part of the Belle Isle dome does not have a simple geometric form; several centers of uplift seem to be present; two are reflected in the topography by the north hill and by the west hill. The drilling reveals another on the southwest radius, and the torsion-balance data suggest another on the east-southeast radius. The flank of the cap is scalloped correspondingly, convex around the centers of uplift and concave between. The scalloping is reflected in the topography of the northwest flank of the island. The west radius lies in the concavity between the respective areas of the northwest and southwest centers of uplift. In the effect on the gradient, the excess of mass in the convexity of the area of these centers of uplift partly compensates for the deficiency of mass in the intervening concavity. The calculations, therefore, predict too much cap rock in the area of the concavity. Conversely, the calculations predict too little cap rock for a line of profile down a convex zone.

CONCLUSION

The Belle Isle torsion-balance survey affords an example of an average successful application of the torsion-balance method to the

quantitative problem of the determination of the dimensions of the upper part of a shallow salt dome. The quantitative predictions were in error by 27-40 per cent, but, qualitatively, the work undertaken was accomplished completely by the balance. In other surveys with the torsion balance, equally good and better results have been obtained. In a survey to determine whether or not at Bryan Heights cap rock might be present on the flanks, the predicted depths proved to be in error by +200-300 feet at depths of 1,500 feet; however, in our report, we had estimated the probable accuracy of our predictions at approximately 40 per cent, but, rather to our surprise, the subsequent drilling proved the accuracy of the predictions to be nearly 60 per cent and cap-rock masses which we somewhat hesitatingly predicted proved actually to be present. In the Hoskins Mound survey, the errors in the predicted depth at four points were proved to be respectively 7, 5, 2, and 0.7 per cent (9).

The accuracy of quantitative calculations of this type decreases with the depth to the top of the anomalies, provided that the density situation remains constant. Geologically, the density may change with depth, and through the complication of the density situation, the accuracy of quantitative calculations through a certain vertical zone may increase with depth. The cap rock at all depths in the Gulf Coast is heavier than the surrounding sediments, but, compared with the salt, the sediments are slightly lighter or of almost the same density at the surface and become progressively denser with depth and at great depth are heavier than the salt. At certain depths, therefore, there is a neutral zone in which the salt can not be detected by gravitational measurements. Below those depths the presence of the salt can be detected by gravitational measurements and the accuracy of quantitative calculations in regard to dimensions of the salt through a certain vertical zone increases with depth, although on account of the law of decrease of accuracy with depth, the absolute accuracy may be very low. Practically, the dimensions of the cap rock can be calculated with fair accuracy for depths less than 3,000 feet and for any domes in the Gulf Coast area; but, on account of the enormously greater thickness of light sediments near the coast and their low specific gravity, predictions in regard to the dimensions of the salt of the domes near the coast are nearly valueless. Surveys across the inland domes of the coastal group suggest that calculated predictions in regard to the salt may be of some use.

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SOME RESULTS OF MAGNETOMETER SURVEYS IN CALIFORNIA¹

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ABSTRACT

The writer describes magnetic conditions associated with some typical structural features in California,—an anticline, a syncline, an outstanding magnetic feature in the San Joaquin Valley, a buried fault near Mount Diablo, a part of Ventura County, and Kettleman Hills.

INTRODUCTION

Magnetometer work was begun in California by the Standard Oil Company of California on January 1, 1927. Acknowledgment is here made to officials of the company for permission to publish, to H. N. Herrick of the Research and Development Department of the company for his assistance and criticism in the preparation of this paper, and to all members of the geophysical field parties in California.

General conditions for use of magnetic geophysical methods in California are good, as there is marked variation in the magnetic susceptibility of the sedimentary rocks of economic interest. In the Tertiary rocks, the magnetic susceptibility varies from 14×10^{-6} in the Saugus of the Upper Pliocene to $4,120 \times 10^{-6}$ in the vivianitic sandstone of the McKittrick group of the Pliocene. This variation is sufficient to give a definite magnetic contrast at several horizons. "Magnetic marker beds," such as this vivianitic sandstone, beds of volcanic tuff and interbedded basaltic flows, extending throughout considerable areas, have been found, which are sufficiently thick and magnetic to cause anomalies of several hundred gammas at surface exposures and recognizable indications under deep cover.

The Cretaceous rocks, especially the Knoxville, on the average, are somewhat more uniformly and strongly magnetic than the Tertiary. The Jurassic (Franciscan) is much more magnetic than either the Ter-

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tiary or Cretaceous and contains irregular masses of basic volcanic rocks, in many places altered to serpentine, which have a magnetic susceptibility as great as $7,000 \times 10^{-6}$, so large as to obscure results on younger beds in the vicinity.

Of the pre-Jurassic rocks in California, the granites, both of the Sierra Nevada and the Coast Ranges, generally have a susceptibility less than 200×10^{-6} , but in many places they contain large bodies of darker rock of gabbroid appearance that are intensely magnetic—sufficiently so that a small hand specimen deflects a compass needle. Many of the metamorphic rocks of the Sierra Nevadas also are extremely and irregularly magnetic. This must be kept constantly in mind in attempting magnetometer work in the San Joaquin Valley, particularly.

The chief practical application of magnetic methods in California has been in tracing known structural features, such as faults and "magnetic marker beds" which present eroded edges on the flanks of folds, from places where they can be seen into regions covered by alluvium. It is not safe in the present stage of the art to attempt to interpret magnetic data without some support either from surface geology or from well logs. It is necessary always to keep in mind that the observed results are affected by all the material beneath, so that many anomalies caused by the formations of principal interest are obscured by unrelated conditions below them in rocks of greater magnetic permeability. For example, it would be very poor engineering to attempt to interpret in terms of structure either a magnetic or a gravity survey of an area known to be underlain by Franciscan rocks at a depth of less than 5,000 feet, because very magnetic and dense bodies of basic igneous rock are probably distributed irregularly within.

Most work consists of measurements and mapping of the vertical component of the earth's magnetic field. For recognizing faults not known by surface evidence, and for other special problems, measurements of horizontal intensity also are required, but are made only where the vertical data indicate that they are necessary for use in interpretation. Ordinary common sense should be used in laying out magnetic surveys, so that time will not be wasted in attempting to solve problems to which the method is unsuited. For most useful results, the following conditions must exist.

1. The rocks of economic interest in the problem must have magnetic contrast, that is, must contain some beds known to be markedly more or less magnetic than the average.

2. The feature sought must have broken or deformed the strata so as to have caused a considerable difference in elevation of some bed of marked magnetic characteristics within the limits of the survey. As an illustration, it is a waste of time to try to trace magnetically a fault of small vertical displacement in the Kern River formation, which has little magnetic contrast.

Field parties.—Our practice in California is to have a party consisting of two geologists, one car, and two vertical magnetometers. This is found more economical because two readings with different instruments can be taken at the same time within a short distance of each other and their values averaged if within a few gammas. This method establishes the value of the point without further checking, and informs the operator immediately if either balance is out of adjustment.

INTERPRETATION

Presentation of results.—In order to interpret the results of a magnetic survey, it is necessary to show the values determined by the work in their true relation to topographic and known geological features on a map of the area surveyed. We have used the following methods.

1. Peg model of vertical intensities. If enough points have been occupied, the tops of the pegs show a magnetic surface from which much can be inferred about the course of faults, magnetic marker beds, and other structural features (Fig. 1). A model of this type is inconvenient to make, transport, or file, and can be shown in the report only by photographing it.

2. Celluloid profile model of vertical intensity. This is made by placing a large sheet of celluloid over a map and cementing to the celluloid cover profiles cut from the same material representing the vertical intensities to scale above each station.

This type of model is more useful than the foregoing because the celluloid is transparent and does not obstruct a view of the map as the pegs do. It is serviceable as a guide in preparing magnetic contour maps because the magnetic surface can be seen without use of the imagination. It has the disadvantages that it can not be easily transported and can be included in reports only by photographing it (Fig. 4).

3. Magnetic contour maps. In this method of presentation, contour lines are drawn connecting points of equal vertical intensity exactly as contour maps of topography are made. Contour maps are easily made and do not greatly detract from the original map on which the contours are drawn. The contours show all the major features and a great many of the smaller features.

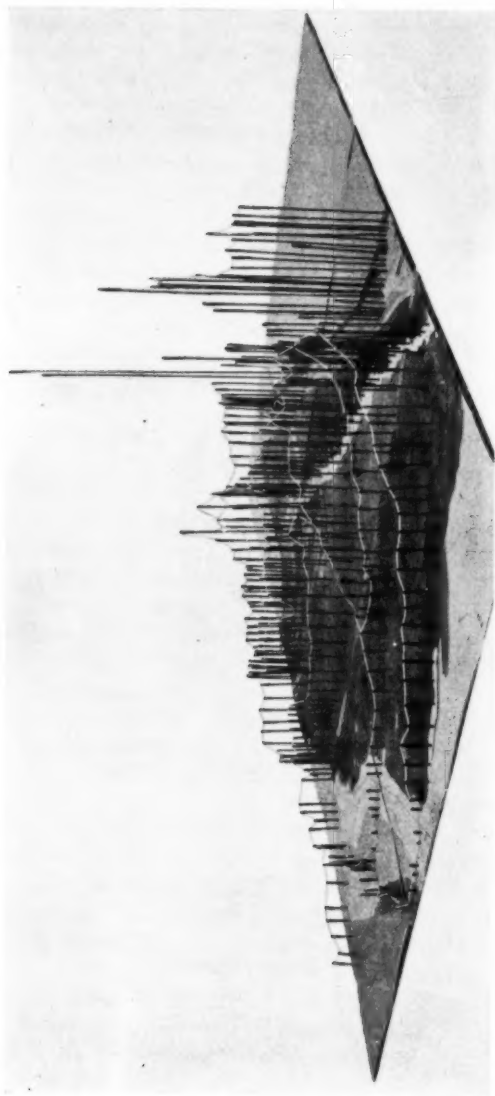


FIG. 1.—Peg model of vertical magnetic intensities from Salinas River to Peachtree Valley across San Andreas fault, southeast of King City, Monterey County, California.

This is probably the best method of showing actual results, and is undoubtedly the best when it is desirable to show the regional trend of folding. During the last few years all the results of our work have been reported in the form of contour maps, as they can be readily extended from area to area throughout large expanses of country and placed on a regional map with some very interesting results.

RESULTS OF MAGNETOMETER SURVEYS IN CALIFORNIA

It would be impossible to publish the results of all the magnetometer surveys we have made in California during the last four years; therefore, only a few of them are offered here. They are chosen because the results are type pictures of known geological conditions, such as the Raven Pass anticline and the White Creek syncline, and the others submitted show the interpretation of magnetometer surveys as carried from known geological features to the unknown.

The following work on known structures was done to test the vertical and horizontal magnetometers so as to use the resulting data in interpreting future results in areas covered by alluvial deposits.

RAVEN PASS ANTICLINE

This anticline trends almost N. 45° W. for a considerable distance, but the location chosen for the magnetometer survey was at the junction of Sections 29, 30, and 31, T. 26 S., R. 18 E. (Fig. 2).

The oldest beds exposed along the axis are the Cretaceous, with the younger Vaqueros and Monterey shale resting unconformably on both flanks. The anticline is apparently symmetrical, the dips ranging from 40° to 50° on both flanks. From surface observations there does not seem to be any faulting in the Cretaceous. As previously mentioned, the Cretaceous is strongly magnetic and the Miocene shales weakly magnetic. Therefore, an anticline in these contrasting formations should give a type picture of the behavior of the vertical intensities and the vectors of disturbance.

Results.—Both the vertical intensities and the magnetic vectors of disturbance were plotted. The vertical intensity curve rose from an intensity of 15 gammas over the Monterey shale on the extreme northeast end of the line to 110 gammas at the axis. From the axis southwestward, the intensity curve fell to 50 gammas over the Monterey shale. A short distance southwest of the axis, the vertical intensity curve gave a sharp "kick" to a maximum of 125 gammas, which strongly suggested a small fault. As stated before, no fault could be traced on

the surface because of the loose soil covering the surface. An erratic dip of 40° N. in the south flank lends support to this small fault.

All the vectors of disturbance, when plotted at each station, point toward the axis of the fold, the angle of each vector with the horizontal becoming steeper as the axis is reached until, at the axis, the vectors are almost perpendicular.

WHITE CREEK SYNCLINE

This syncline, 20 miles northwest of Coalinga, trends N. 60° W. for a considerable distance, but the locality chosen for the magnetometer line was in the SE. $\frac{1}{4}$, Sec. 23, T. 19 S., R. 13 E. (Fig. 3).

The Cretaceous beds are folded into an asymmetrical syncline with the north flank dipping 65° and the south 45° . Folded in the trough of these older beds and overlapping them is the Etchegoin. The axis of the syncline in the Etchegoin can be determined on the ground because of the outcropping on both sides of the axis of the characteristic *Glycimeris* bed. The Etchegoin is moderately magnetic and the Cretaceous is strongly magnetic.

Results.—The plotting of the vertical intensities and the magnetic vectors of disturbance showed a condition the reverse of those plotted from the Raven Pass anticline. The vertical intensities, plotted in gammas, showed a curve with its lowest point at the axis of the syncline where the Etchegoin would be at its thickest over the magnetic Cretaceous. The highest points in the curve naturally occurred at the end of the line directly above the Cretaceous.

The vectors of disturbance point vertically down at the axis; and outward from this point toward the more magnetic Cretaceous beds.

WALNUT CREEK FAULT (FIG. 4)

The Walnut Creek area comprises an alluvial valley bounded on the west by Martinez Ridge, and on the south by Shell Ridge, both of which expose Tertiary rocks. The structural features consist of two major faults traversing the valley, approximately at right angles to each other, and several minor faults. On the northeast side Cretaceous rocks are exposed and the valley is surrounded on the other two sides by the Eocene rocks. This is an ideal condition, as the Cretaceous in Walnut Creek is very magnetic, the Eocene is weakly magnetic, and these formations are cut by several faults.

The work was begun by running lines with the magnetometer across the supposed location of a major fault, marked on the map as the Martinez-Shell Ridge fault. The position on this is established by surface

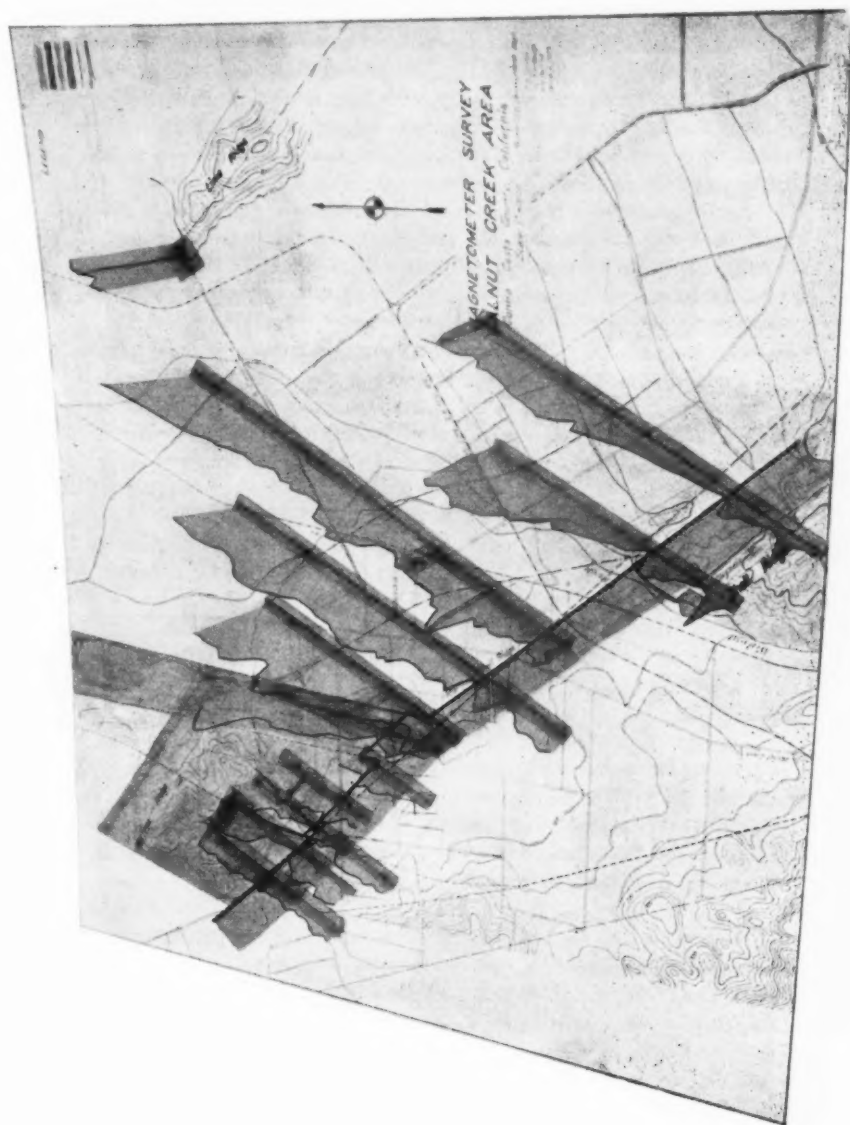


FIG. 4

evidence on both sides of the valley, but it is concealed by a deep cover of alluvium for several miles in the location chosen for an accurate determination of the trace of this fault. The procedure was to run lines at intervals of $\frac{1}{4}$ mile across the approximate location of the fault. The average length of the lines is approximately 1 mile. Magnetometer readings were recorded at each 200 feet. The course of the lines was N. 27° E., approximately at right angles to the strike of the fault.

As the work continued, it became increasingly evident that the Cretaceous area northeast of the fault showed much stronger vertical intensity than the Eocene on the southwest. Celluloid profiles showing vertical intensity plotted to scale were affixed to the map along the lines of survey, and the surface, outlined by the edges of these profiles, indicated a sort of magnetic plateau over the supposed Cretaceous area. As the valley floor is concealed beneath alluvium, a short line was run across the point of Lime Ridge where there are outcrops of rocks known to be Cretaceous, and high vertical magnetic intensities were found corresponding with those in the doubtful region. A sharp depression in the magnetic profiles near the assumed position of the fault was followed to the hills and proved to occur at the known location of the fault. This sharp depression in the magnetic profile has therefore been assumed to indicate the trace of the fault throughout the part covered by alluvium. The shape of the curve at this point is characteristically the same on all the profiles. On the basis of this indication the writer has drawn in the fault line, which in general lies close to that originally assumed, but has two offsets on the north which may have resulted from cross faults supposed to exist at this location, provided the assumptions here followed are correct.

Several of the survey lines have crossed small faults, with much smaller indications. Seemingly there is no property of a fault as such that affects the magnetic instruments, and a fault will probably be indicated by them only where rocks of different magnetic properties have been brought opposite each other, or where a magnetic bed has been offset horizontally in crossing the fault.

Magnetic marker beds.—An inspection of the magnetic profiles shows high points at intervals, which are found to be in definite lines. It is natural to assume that these lie over buried outcrops of beds of stronger magnetic properties than those of adjacent rocks. In order to verify this conclusion some lines were run with observations at short intervals across exposed beds in line with these series of high points on the profiles. It was found that some beds show very high values, which dis-

tinguish them strikingly from the rest of the formation. Two such beds were observed in the Cretaceous, of which the course is indicated by lines connecting high points in the profiles (Fig. 4), and one such bed was found in the Briones. As some of the magnetic anomalies by which these beds differ from the associated rocks amount to as much as 300 gammas, nearly one hundred times the least reading possible with the instruments, they are very conspicuous markers, easily recognizable with the magnetometers. The effect of these magnetic beds is very large and sharply marked where they crop out, and becomes progressively less intense and more widely distributed as the depth of cover increases. Their effect is clearly evident under the deepest cover existing in the Walnut Creek Valley. This depth is not known, but, as indicated by water-well evidence, is probably more than 150 feet.

POSO CREEK, SAN JOAQUIN VALLEY, CALIFORNIA (FIG. 5)

In the vicinity of Poso Creek, the magnetometer outlined an outstanding magnetic "high" indicating that a strongly magnetic mass, such as gabbro, has been uplifted close to the surface. Confirmation of this fact is supported by the drilling of a well on the flank of this magnetic "high" which entered plutonic rocks at 2,700 feet. The uplifting of this gabbroid mass caused a fault on its north side. Figure 5 shows that in working with such large bodies of magnetic material the effect of the deeper rock can be corrected out. This picture presents the small anomaly, caused by a fault, separated from a large regional variation, caused by a very magnetic large mass in the underlying basement complex.

VENTURA COUNTY

The survey shown on Figure 6 comprises an area of about 35 square miles south and east of Oxnard, California. It is a relatively sandy flat basin flanked on the northeast by the Camarillo Hills and by Round Mountain, an isolated igneous hill in the southeastern part.

There is no doubt that the volcanic rocks are the chief causes of magnetic disturbances in this area. The effect of concentrations of magnetic minerals in terrace material is small and local—in few places more than 20 gammas—and does not mask the major disturbances.

Results of the survey are shown on Figure 6, which gives contours of vertical intensity at 10-gamma intervals. As volcanic rocks are exposed on the southeast rim of the basin, and not at the north, the large disturbances in this part of the Ventura basin are probably the result of underlying bodies of volcanic rock. This interpretation was later sup-

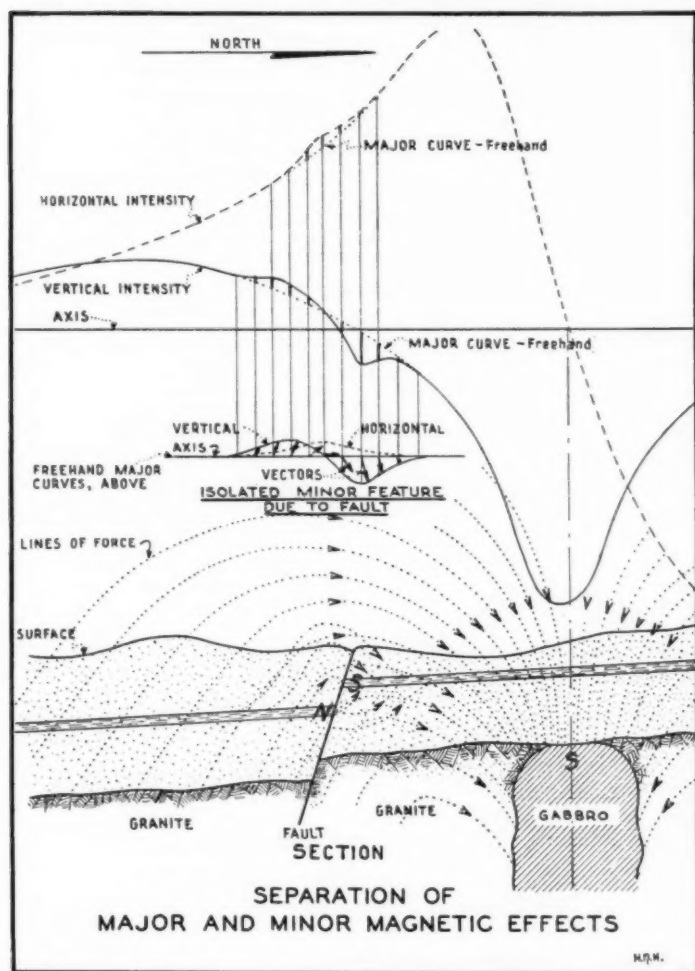


FIG. 5

ported by the results of the drilling of The Texas Company's Eastwood No. 1, 3 miles east of the town of Hueneme, which entered basalt at 1,915 feet. As this assumption was proved correct, it follows that the

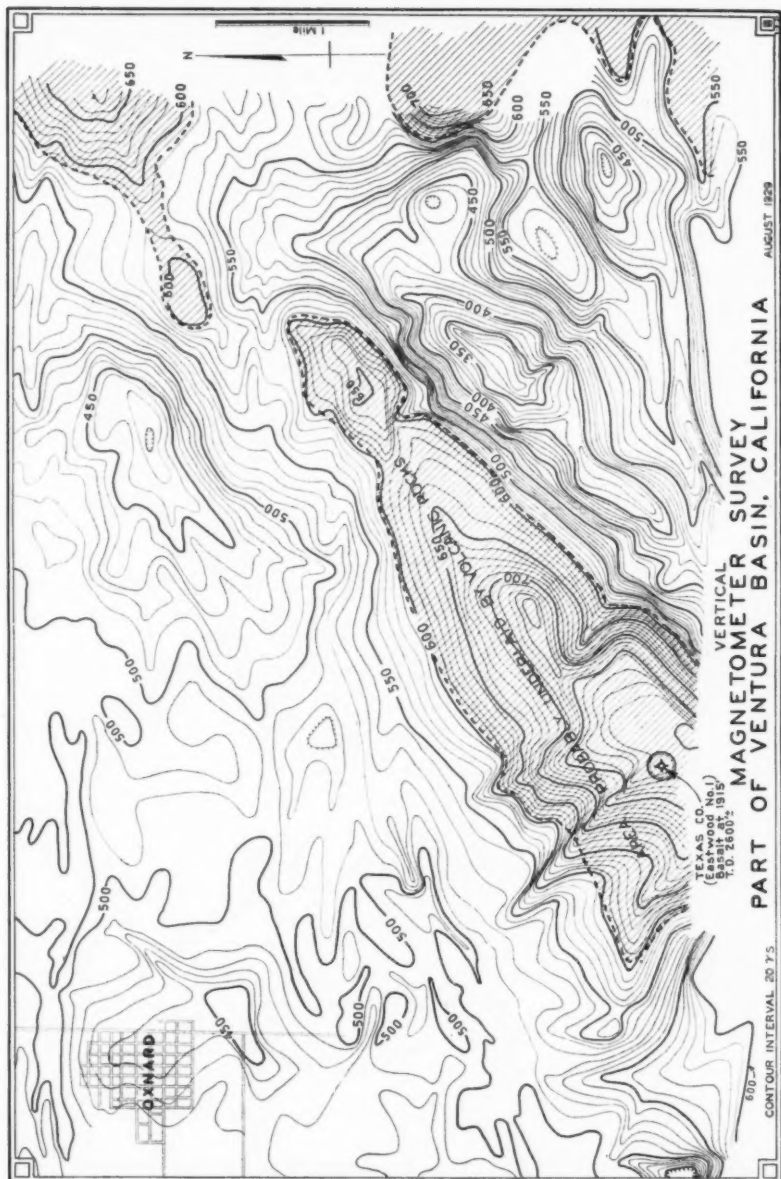


FIG. 6

limits of the volcanic rocks are indicated by the edge of the area of great magnetic intensity as outlined on the map. The magnetic susceptibility of the basalt from the well was determined to be as great as 677×10^6 .

KETTLEMAN HILLS, CALIFORNIA

The Kettleman Hills structure is divided into three separate folds, known as the North, Middle, and South domes. The Lost Hills field is a continuation of the South dome structure and is intimately related to the Kettleman Hills structure. Magnetometer surveys have been made on all the structures. The North and Middle dome surveys are treated separately from the South dome-Lost Hills structure.

NORTH AND MIDDLE DOME

On the North dome the average dip is 35° - 40° on the southwest flank and 25° - 30° on the northeast. Thus the axial plane probably dips toward the northeast slightly. The beds of the Middle dome dip approximately 30° on both flanks. The trend of the two domes is about N. 40° W. and they lie *en échelon*.

There is a very intricate system of faulting, both lateral and cross, along the crest of the structures. Displacements range from a few feet to more than 100 feet in some places. This has resulted in raising or lowering blocks out of their original position. This minor faulting with its consequent disturbance of the magnetic vivianitic sandstone bed, together with its erosion, is largely responsible for some confusion in the magnetic picture.

The Paso Robles formation crops out as an almost complete belt around these domes with the Etchegoin formation exposed beneath. The Etchegoin is exposed along the crest for $1\frac{1}{2}$ miles on both sides of the axis. The Paso Robles is composed of fresh-water beds of ill sorted and little consolidated sands and gravels. The Etchegoin underlying the Paso Robles and occupying the crest of the anticline consists of clays and sands with a coarse blue vivianitic sandstone as the most important member for the magnetic survey.

The "magnetic marker bed" or series of beds of the vivianitic sandstone consists of a blue sand ranging from fine to coarse. It is found so poorly cemented that it is possible to rub it apart with the fingers, though in other places it is hard and resistant. The blue color seems to be caused by a thin coating of hydrous-ferrous phosphate on the individual grains. It is very magnetic and tests made in the field prove that it is polarized. Tests around an outcrop of this sandstone showed readings with a range of 300 gammas in a distance of less than 200 feet.

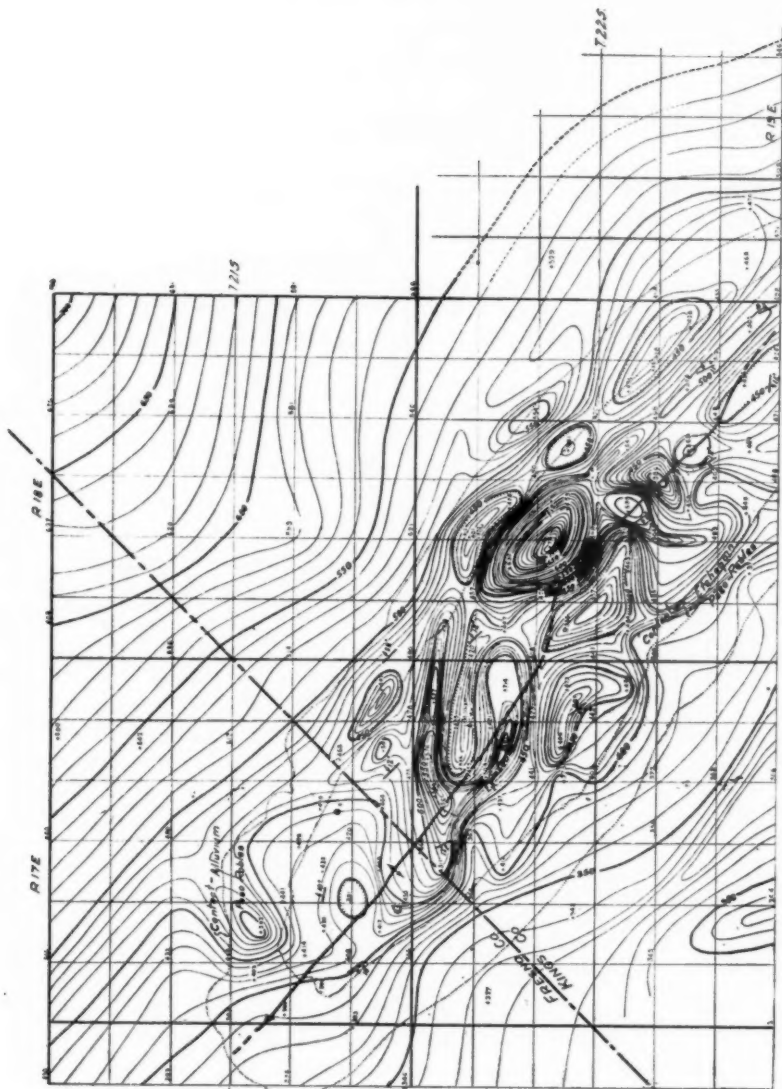
Results of magnetic work.—The magnetic picture (Fig. 7) presented of the North and Middle domes of Kettleman Hills is an irregular one and only general relations may be interpreted from it. We have definitely established the fact that the vivianitic beds cropping out at the surface are definitely polarized and that the presence or absence of these beds controls the magnetic results obtained. Unfortunately, the vivianitic horizon does not occur along definite lines of stratification, but is distributed in lenses and patches throughout the whole series comprising the top of the Etchegoin formation. It is this irregularity of the vivianite which gives such surprising and irregular results. Magnetic anomalies are very large and many abrupt changes of more than 300 gammas were obtained within a radius of a few hundred feet. Differences of readings of more than 100 gammas were obtained on the same outcrop, seeming to indicate that the concentration of magnetic material is decidedly lacking in uniformity and that mass also has some effect. Erosion and some minor faulting cause the operator in some places to be above and in some places to be below the beds furnishing the "kick."

In general, the magnetic contours trend northwest and follow structural contour lines. On the North dome is a series of "highs" along the upturned edges of the blue sandstone with alternate "highs" and "lows" along the axis, depending on whether patches of vivianite are present or not. The beds on the northeast flank of the structure show a well defined series of "highs," but the relationship is not so clear on the southwest flank, nor does the closure north of the Millham well conform to the closure as determined by the geology. There is a well defined series of "lows" along the northeast edge of the structure which may be indicative of fault conditions.

The Middle dome presents a more regular picture with a series of "highs" along the axis. These "highs" even follow the offset or warp of the axis between the two domes. The greater regularity, as shown on the Middle dome, is caused, probably, by the more moderate relief in the topography and greater protective covering over the magnetic beds. It is also possible that the magnetic content of these beds is more uniform than that of those farther north. The results suggest that the magnetic beds are continuous across the axis here.

From the foregoing described results the following conclusions can be drawn.

1. The North and South domes of the Kettleman Hills structure are marked by a zone of intense magnetic disturbance, which conspicuously distinguishes them from relatively featureless surroundings.



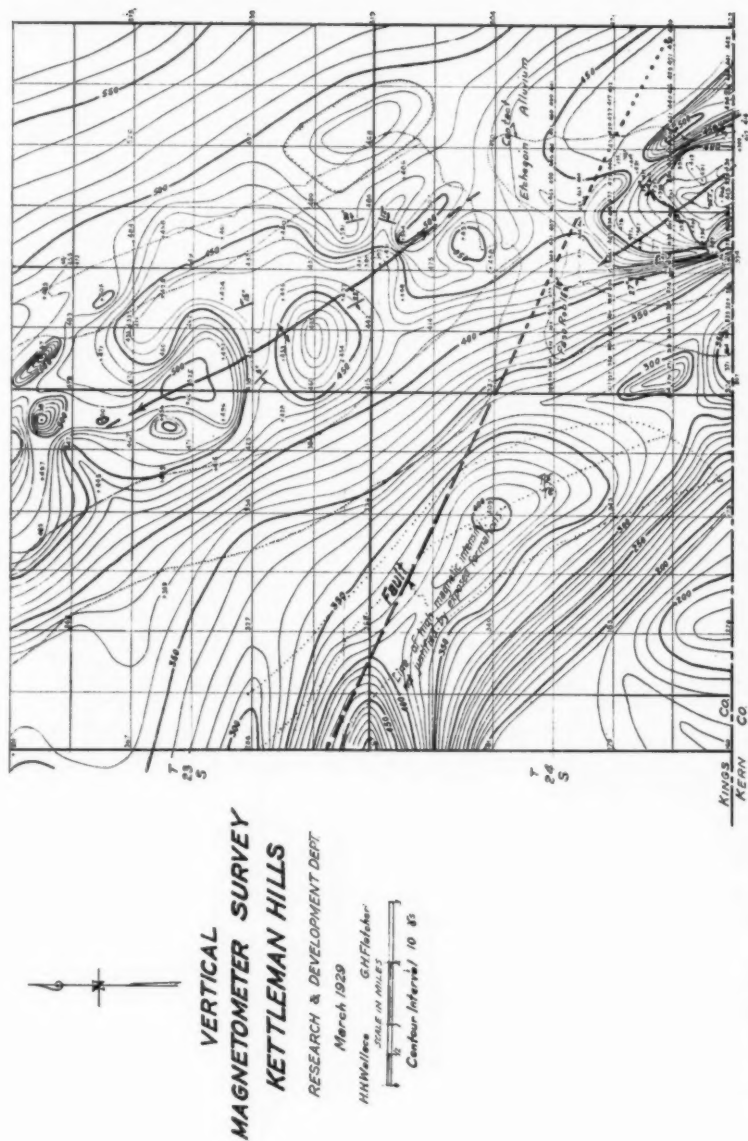


FIG. 7.—Vertical magnetometer survey, Kettleman Hills, California. Upper part shows North dome; lower part Middle dome, and north end of South dome.

2. The North dome shows low intensity along its axis surrounded by high intensities on the flanks over eroded edges of magnetic beds.
3. The Middle dome shows high intensity at the axis, as would be expected from a magnetic bed arched continuously across the structure and not eroded. The obvious inference is that the Middle dome is structurally lower than the North dome.
4. The magnetically active horizon has been identified as the vivianitic sandstone of the upper Etchegoin (McKittrick group) of Pliocene age.
5. It has been discovered that this sandstone is also strongly polarized along definite lines.

SOUTH DOME-LOST HILLS STRUCTURE

The area surveyed is a strip extending northwest-southeast from the northern end of the Lost Hills oil field, Kern County, to and including South dome of Kettleman Hills, Kings County, on the western side of the San Joaquin Valley, California. It ranges from 2 to 4 miles in width and has a length of 14 miles.

The country covered by the survey is one of relatively small relief. The central part is a gently rolling, alluvium-covered plain, slightly sloping downward toward the northeast. At either end of the area are low, rolling hills rising from 50 to 200 feet above the general level of the country. The Lost Hills, from the west side, appear as the crest of a gradually rising plain, but on their eastern side they rise more abruptly and are more prominent features of the landscape.

The only formations exposed are Etchegoin (Pliocene), San Joaquin clays and Tulare (Upper Pliocene), and alluvium.

The folding in the Lost Hills-South dome district is a segment of the long, anticlinal fold, extending northwest-southeast for 60 miles. Folding along this line has also caused the North and Middle domes of Kettleman Hills and the Coalinga anticline. Recurrent movements along the line have occurred since its probable beginning, at the end of Cretaceous time. Gentle folding was repeated at the end of the Eocene. More intense folding recurred at the close of Miocene and Pliocene time.

Surface evidence of the structure is incomplete, because of the mantle of alluvium in the central part of the area. The topographic "high" and surface exposures show the anticlinal origin of the Lost Hills. The trend of the *Mulina* bed, at the top of the Etchegoin, and the dips obtainable at the South dome, disclose the northwestward plunge at that point.

Results of magnetometer survey.—The survey shows a magnetic "low" extending from the Lost Hills to the South dome. A very marked "high" is east of the "low" and extends parallel with it. On the western side of the area, the magnetic "high" is not so great in the south, but northwestward the intensity increases and the changes from "highs" to "lows" become much sharper and more pronounced. This is because the sandstone beds in the Upper Etchegoin cause the magnetic "highs," and in the south the mantle of alluvium is probably thicker, causing a greater masking effect on the magnetic beds. At the South dome the parallel "highs," on either side of the area, swing around and close, conforming to the trend of the *Mulinea* bed.

At the South dome the magnetometer results are substantially the same as those shown by surface and subsurface geology. The trend of the magnetic anomalies conforms with the strike of the beds, and the manner in which the "high" closes on the north is especially convincing. The alternating long, narrow "highs" and "lows," in the northwest, are undoubtedly caused by interbedded sandstones and sandy shales and clays. The magnetic "highs" are on sandstone beds.

The structural axis at the South dome follows a line of magnetic "lows." The "lows" fall midway between magnetic "highs" caused by magnetic sandstone beds near the Etchegoin-San Joaquin clays contact. Erosion has removed these magnetic beds from along the axis of the anticline, leaving their truncated edges on the flanks of the structure, with less magnetic beds in the center. This explains the relationship of the anomalies to the structure in this area.

By analogy with conditions existing at the South dome, the axis of the structure can be located southward, connecting with the Lost Hills field. Immediately north of the Lost Hills oil field, the magnetic "low" swings sharply westward and turns northwest to the South dome. As the magnetic anomalies are similar to those at the South dome, the axis of the anticline probably follows the magnetic "low."

From the foregoing evidence the following conclusions can be drawn.

1. It is possible to show the location of the axis of the Lost Hills-South dome anticline.
2. The structure is continuous from the Lost Hills to the South dome.
3. The position of the axis, according to the magnetometer, corresponds fairly well with the geologic axis, excepting north of the Lost Hills, where it deviates and causes an offset in the trend of the axis.

4. A pronounced feature of the survey is that the trend of the magnetic anomalies conforms with the strike of the beds in the South dome, and the manner in which the "high" closes on the north is most convincing.

5. The buried outcrop of an eroded magnetic bed can be traced completely around the South dome, including the Lost Hills field.

6. The survey shows a magnetic "low" extending from the Lost Hills to the South dome, with a marked "high" east of the "low" and paralleling it.

7. The magnetic anomalies at the South dome have a higher intensity than the rest of the area, because the sandstone beds in the Upper Etchegoin cause the magnetic "highs," and at the south the mantle of alluvium is thicker and the Etchegoin thins out, thus decreasing the intensity.

MAGNETIC DISTURBANCE CAUSED BY BURIED CASING¹

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ABSTRACT

A vertical string of casing becomes magnetized by induction under the influence of the terrestrial magnetic field. For theoretical investigation we may treat such a casing as a bar magnet having an exaggerated ratio of length to diameter. Formulae are derived, based on the fundamental law of Coulomb, to express the anomalous components of the magnetic elements in different horizontal planes and at different radial distances from the casing head. Curves representing these equations are shown. Graphical illustrations of the composition of these anomalous components and the normal components of the earth's magnetizing field are included, together with typical experimental data obtained in the field.

INTRODUCTION

In the investigation of magnetic phenomena directly associated with oil- and gas-producing fields, as well as in attempting to map geologic structure along the boundaries of such areas, the magnetic distortion traceable to buried casing becomes of vital importance to the geophysicist.

As many of the empirical data that furnish valuable criteria for interpretative analysis must necessarily be obtained in regions where subsurface features have been disclosed by existing wells, it seems that a thorough understanding of the disturbing effect of this metal is essential to a proper appreciation of the experimental results.

In this paper it is intended to present briefly the theoretical aspects of the problem and to include such field observations as are considered representative of the cases thus far investigated.

The writer wishes to acknowledge his indebtedness to Randolph H. Mayer for his valuable assistance during the preparation of this paper, and to express his appreciation to John S. Ivy for the data furnished regarding the location and completion dates of wells in the Sligo field.

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²Geophysicist, William M. Barret, Inc., Giddens-Lane Building. Introduced by D. M. Collingwood.

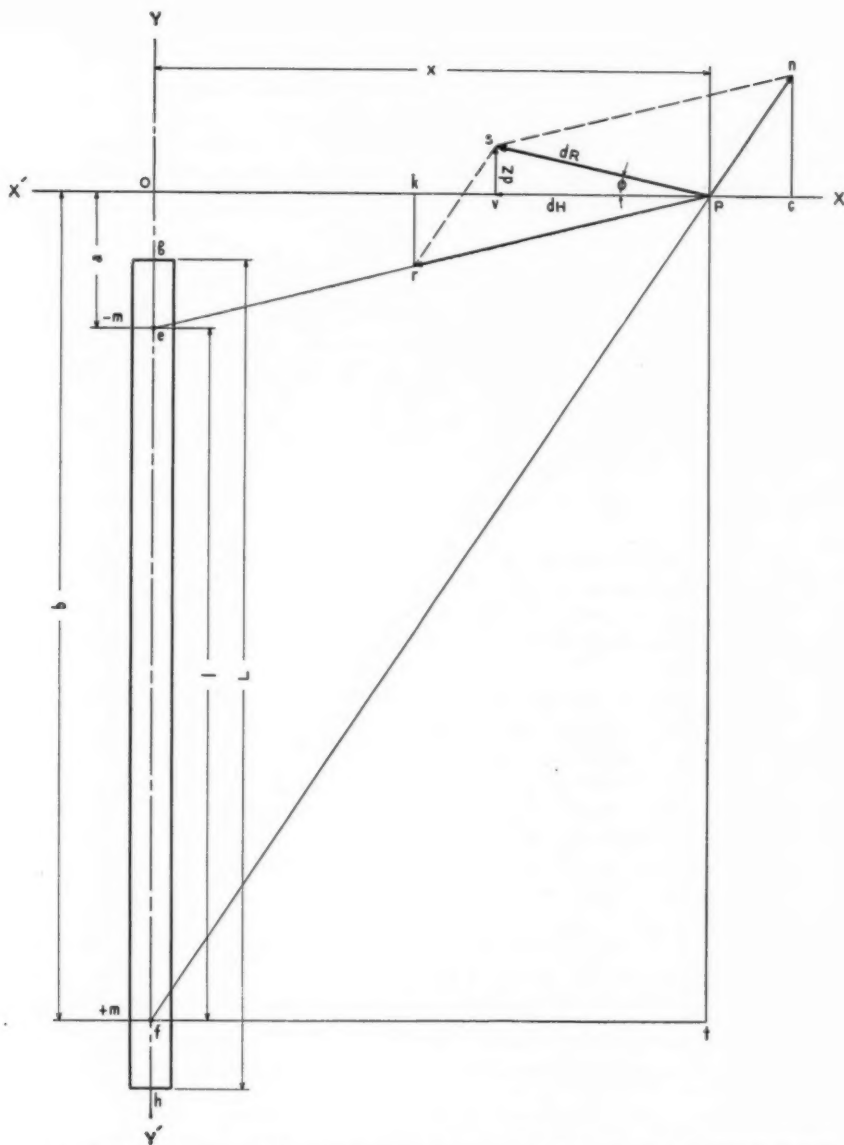


FIG. 1.—Vector representation of the anomalous magnetic field at point P, caused by vertical string of magnetized casing gh .

THEORETICAL CONSIDERATIONS

The magnitude and direction of the resultant magnetic field near the casing head of a vertical string of pipe depends on the physical composition and proportions of the metal, the mechanical and thermal stresses involved, the perpendicularity of its vertical axis, the intensity and direction of the earth's magnetizing field, and the physical and magnetic characteristics of the subsurface media.

Referring to Figure 1, let us consider the vertical string of casing gh , having its major axis lying in YY' . It is evident that by induction the terrestrial magnetic field will establish a negative pole near the upper end of the casing and a positive pole near its lower end. Assuming the surrounding media to have unit permeability, and denoting the positive and negative pole strengths by $+m$ and $-m$ c. g. s. units respectively, we have

$$\begin{aligned} +m &= -m = \frac{\pi}{4} (d_2^2 - d_1^2) kZ \\ &= AkZ \end{aligned} \quad (1)$$

where d_2 is the external diameter of the casing in centimeters;
 d_1 is the internal diameter of the casing in centimeters;
 A is the cross-sectional area of the casing in square centimeters;
 k is the susceptibility of the casing material;
 Z is the vertical component of the earth's magnetic field in gauss.

For our purposes we may regard the casing as a bar magnet having the length L centimeters and distance between poles l centimeters. The magnetic moment in c. g. s. units will be given by

$$M = ml \quad (2)$$

Let us consider the strength and direction of the anomalous field at the point P , lying in OX , caused by the vertical string of magnetized casing gh . The resultant force Ps at the point P will be determined in magnitude and direction by the vectors Pr and Pn , the former representing the attractive reaction on a unit positive pole placed at P , caused by $-m$, and the latter representing the repulsive reaction of the pole, $+m$. The solution of the problem is simplified by solving for the vertical and horizontal components dZ and dH , after which the resultant force dR and the angle of inclination $d\phi$ may be readily determined.

Denoting the permeability of the media surrounding the casing by μ , we have by Coulomb's law

$$Pn = \frac{m}{\mu fP^2} = \frac{m}{\mu (b^2 + x^2)}$$

$$Pr = -\frac{m}{\mu cP^2} = -\frac{m}{\mu (a^2 + x^2)}$$

As the triangles Pcn and fOP are similar, we may write

$$\frac{Pn}{cn} = \frac{fP}{Of} = \frac{(b^2 + x^2)^{\frac{1}{2}}}{b}$$

$$\text{or } cn = \frac{Pn \cdot b}{(b^2 + x^2)^{\frac{1}{2}}}$$

Substituting the value of Pn and reducing, we have

$$cn = \frac{bm}{\mu (b^2 + x^2)^{\frac{3}{2}}} \quad (3)$$

Similarly, it is seen that

$$\frac{Pr}{kr} = \frac{cP}{Oe} = \frac{(a^2 + x^2)^{\frac{1}{2}}}{a}$$

$$\begin{aligned} \text{and } kr &= \frac{Pr \cdot a}{(a^2 + x^2)^{\frac{1}{2}}} \\ &= -\frac{am}{\mu (a^2 + x^2)^{\frac{3}{2}}} \end{aligned} \quad (4)$$

Combining expressions (3) and (4) we find the vertical component of the anomalous field at the point P to be

$$dZ = \pi s = \frac{bm}{\mu (b^2 + x^2)^{\frac{3}{2}}} - \frac{am}{\mu (a^2 + x^2)^{\frac{3}{2}}} \quad (5)$$

In like manner it may be shown that the horizontal component of the anomalous field at the point P is

$$dH = P_v = \frac{xm}{\mu (b^2 + x^2)^{\frac{3}{2}}} - \frac{xm}{\mu (a^2 + x^2)^{\frac{3}{2}}} \quad (6)$$

Also, the resultant may be found from (5) and (6), thus

$$\begin{aligned}
 dR = Ps &= \left[(dZ)^2 + (dH)^2 \right]^{\frac{1}{2}} \\
 &= \frac{m}{\mu (a^2 + x^2) (b^2 + x^2)} \left[(a^2 + x^2)^2 + (b^2 + x^2)^2 - \right. \\
 &\quad \left. 2 (ab + x^2) (a^2 + x^2)^{\frac{1}{2}} (b^2 + x^2)^{\frac{1}{2}} \right]^{\frac{1}{2}} \quad (7)
 \end{aligned}$$

The foregoing equations give values for the vertical, horizontal, and resultant forces of the anomalous field in gauss when the distances are expressed in centimeters and the pole strengths in c. g. s. units.

The angle between the resultant dR and the OX -axis is termed the inclination, or dip, and may be found as follows:

$$\tan d\phi = \frac{dZ}{dH} = \frac{b (a^2 + x^2)^{\frac{1}{2}} - a (b^2 + x^2)^{\frac{1}{2}}}{x [(a^2 + x^2)^{\frac{3}{2}} - (b^2 + x^2)^{\frac{3}{2}}]} \quad (8)$$

In Figure 2 are shown curves representing equations (5) to (8) inclusive. These data were prepared from an investigation of a 206-foot vertical string of 10-inch casing, having its upper end level with the earth surface. The pole strength of the casing was determined experimentally by measuring the vertical intensity anomaly directly above the pipe and solving for m in equation (5), it being assumed that $l = 0.833 L$, and that the media surrounding the casing were of unit permeability. At a point 102.4 centimeters above the upper end of the pipe the anomaly was found to be 32,402 gammas.¹

An examination of these curves reveals certain interesting characteristics. It is seen that the dZ and dR curves reach their maximum positive values directly over the casing, at which point they are numerically equal, because for this position the dH component is zero. At a radial distance of approximately 100 feet from the axis of the casing, dZ becomes zero and at 157 feet attains its maximum negative value of -102 gammas; at 260 feet the effect is reduced to -78 gammas. At a distance of 17 feet from the casing the dH component reaches its maximum amplitude of 12,500 gammas and at 75 feet appears equal to dR , because of the scale chosen. When the distance is increased to 260 feet the dH and dR values are 75 gammas and 108 gammas, respectively.

¹1 gamma = 10⁻⁵ gauss.

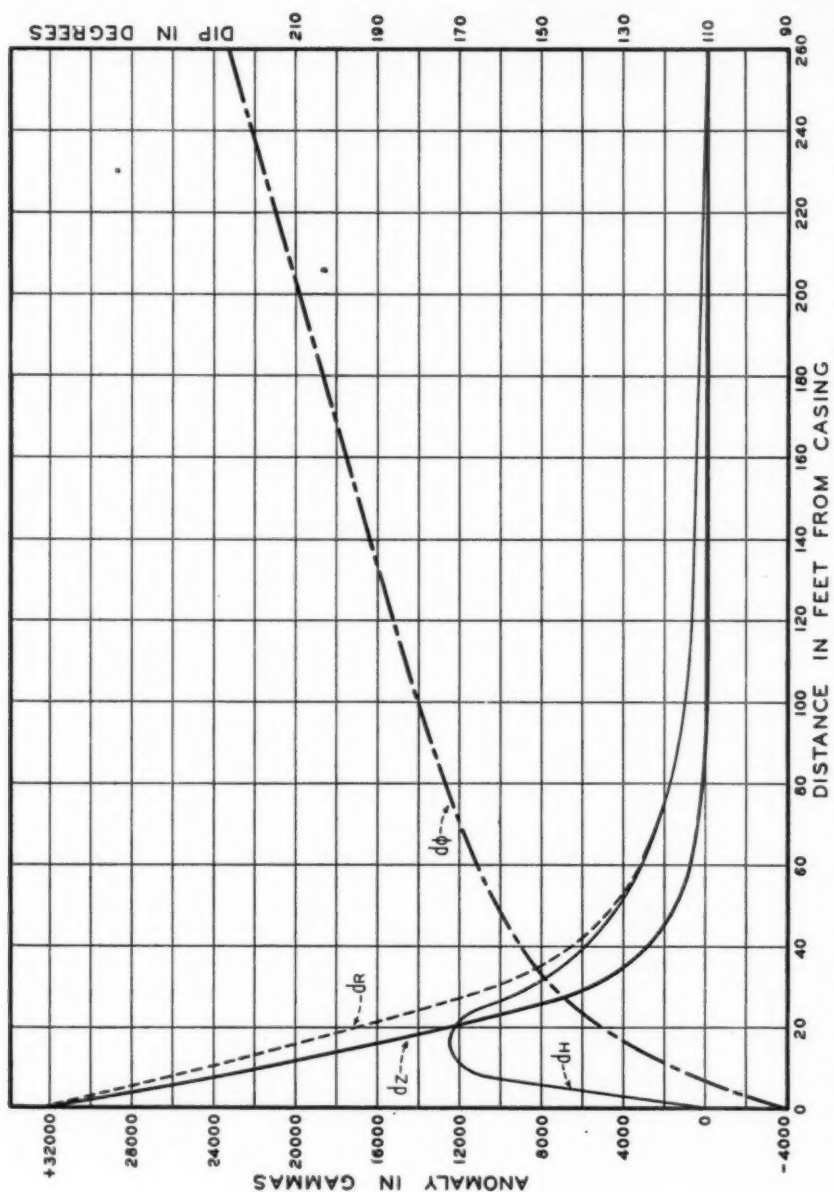


FIG. 2.—Theoretical curves representing equations (5) to (8) inclusive, and showing surficial variation of anomalous magnetic field caused by a 206-foot vertical string of 10-inch casing.

Directly over the casing the dip is 90° , indicating that the resultant vector is vertically downward and as the distance increases the dR vector rotates in a clockwise direction, becomes horizontal when $d\phi$ is 180° , and has moved 46° into the second quadrant of the rectangular coordinate system at a radial distance of 260 feet. The magnetic declination, which may be defined as the angle between the astronomic meridian and the magnetic meridian, will clearly depend on the azimuth selected for the profile, although the shape of the other curves will be the same regardless of the azimuth chosen.

The composition of these anomalous components with the normal terrestrial components determines the absolute values of the magnetic elements in the region surrounding the casing head. Let us next consider these resultant effects, which are graphically illustrated for a magnetic north-south traverse in Figure 3. The Z component at any point, as would be anticipated, represents the algebraic sum of the anomalous vertical intensity and the normal vertical intensity which would exist but for the presence of the magnetized casing. The normal vertical field strength, determined before the casing was set, was found to be 49,552 gammas and the maximum departure from this normal value occurs directly over the casing, where it becomes 81,954 gammas. The normal value of the resultant R was 55,489 gammas and its peak intensity of 87,891 gammas is coincident with the Z curve. The north and south parts of the R , H , and ϕ profiles are not symmetrical with respect to the casing axis, because these curves are determined by the vector composition of the anomalous and normal components. The maximum departures of the horizontal element, from the normal value of 24,974 gammas, occur in the immediate vicinity of the casing head, where the H curve indicates a variation of 25,000 gammas from a point 13 feet south to a position 15 feet north of the pipe. As for each azimuth the dH component is directed toward the casing, it is understood that the numerically lower values of H , for the north part of this profile, represent a subtractive effect, but south, the components are additive. Points of maximum and minimum for the angle of dip, which has a normal value of $63^\circ 15'$, occur adjacent to the casing, the relatively larger angles of inclination for the north part of the ϕ profile being traceable to the decrease in horizontal intensity. The different curves indicate that the magnetic elements have returned to substantially normal values at 260 feet in either direction from the casing. The declination profile is not shown because this element is subject to no variation, other than the

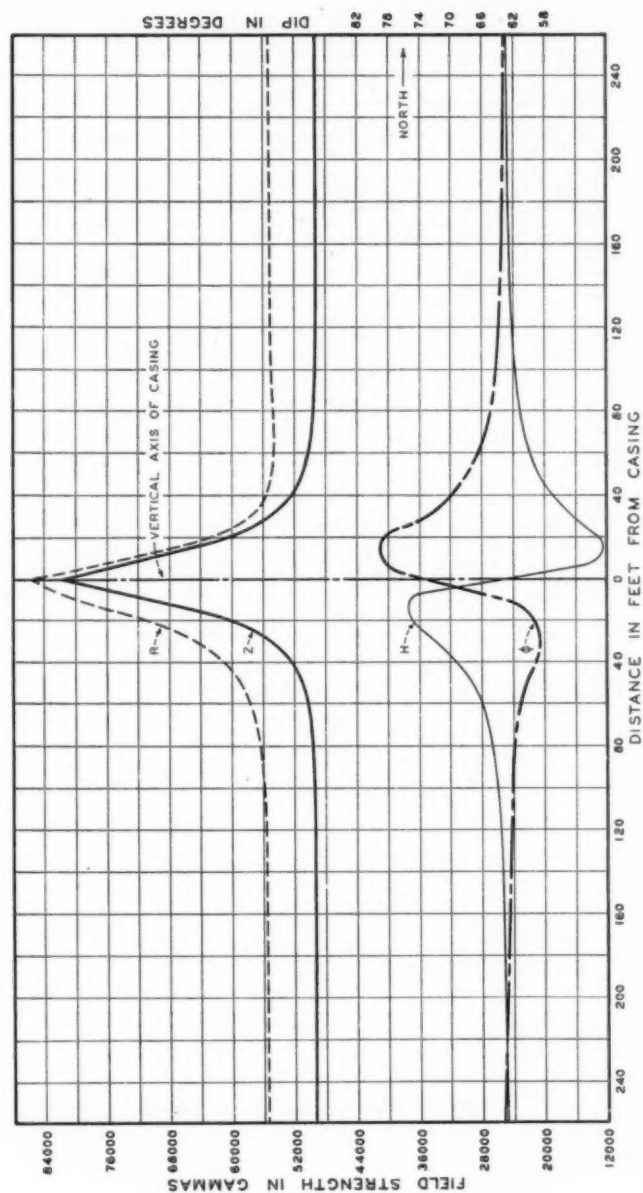


FIG. 3.—Composition of anomalous and normal values for a magnetic north-south traverse across a 200-foot vertical string of 10-inch casing.

constant areal value of $7^{\circ} 50'$ east, along the magnetic north-south azimuth.

Figure 4 shows the composition of the anomalous and normal components for a magnetic east-west traverse. The symmetry of the Z , R , H , and ϕ curves, as well as the relatively minor disturbance of the horizontal component and the dip, are apparent. The declination curve indicates a variation of $52^{\circ} 30'$ from a point 15 feet west of the casing to a corresponding position east.

EXPERIMENTAL RESULTS

To check the validity of the derived equations it was decided to take a series of actual observations along a magnetic north-south profile across the 206-foot string of casing represented by the foregoing theoretical curves. Vertical intensity measurements were chosen for the field investigations for the reason that, in the light of applied geomagnetics, this component assumes major importance. Further, it was felt that a comprehensive study of this single element would serve to test the authenticity of the various formulae in view of the mathematical relation between the several components. We therefore confine our comparison of the theoretical and experimental data to the vertical element.

For these measurements a Schmidt vertical field balance was used, the magnetic system being maintained at a constant elevation of 102.4 centimeters above a horizontal plane, through the upper end of the casing, to conform with the distance Og of Figure 1. The results for the north and south parts of the traverse agreed within the instrumental order of accuracy, mean values for the various positions being shown in Table I.

TABLE I

<i>Distance in Feet</i>	<i>DZ in Gammas</i>
0	+32,402
3.2	+19,470
6.6	+ 6,731
12.0	+ 1,988
22.0	+ 434
32.1	+ 158
46.0	+ 37
56.0	- 6
81.0	- 39
118.5	- 29
147.0	- 14
260.0	0

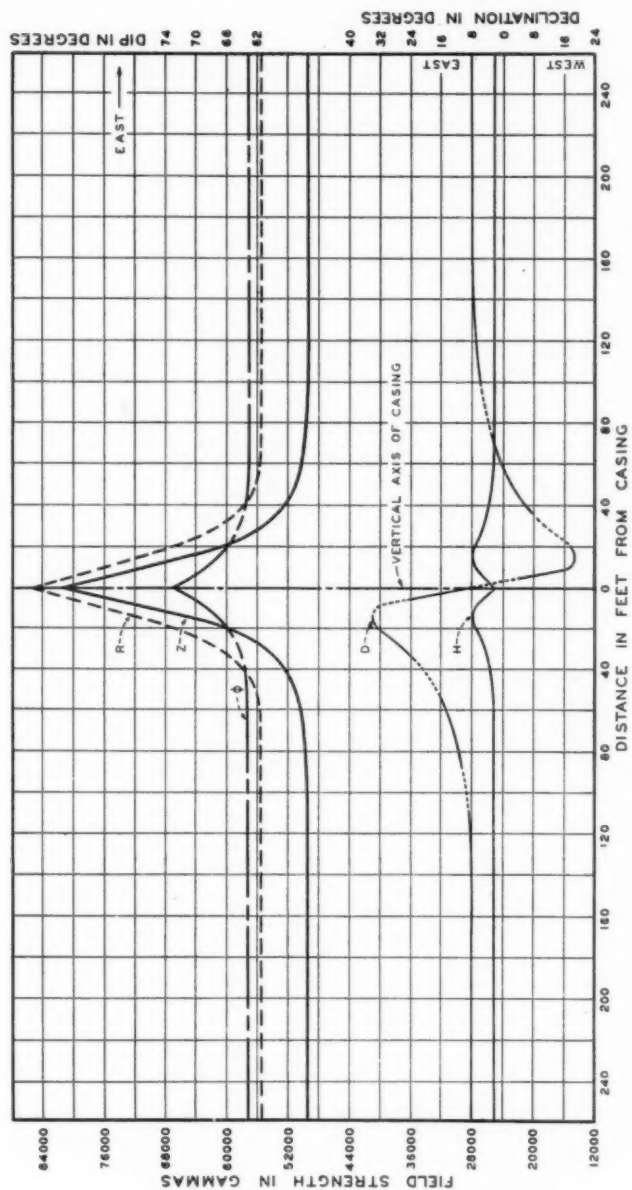


FIG. 4.—Composition of anomalous and normal values for a magnetic east-west traverse across a 200-foot vertical string of 10-inch casing.

A graphical representation of these data is illustrated by the heavy curves of Figure 5, an enlarged scale for the lower values of *DZ* being included for the purpose of disclosing the negative part of the curve. For these profiles the line of zero anomaly indicates the normal vertical intensity for the area, and it is seen that the *DZ* curve intersects this reference line at 54 feet, returning to normal value at approximately 200 feet. It is evident, from an inspection of equation (5), that a change in the elevation of the magnetic system of the variometer, with respect to the casing, would result in a variation of the vertical intensity anomaly. This was verified for the position 32.1 feet north of the casing head, where it was found that a change in elevation of 44 centimeters caused *DZ* to increase 34 gammas, the higher intensity corresponding with the lower elevation.

Let us now proceed to examine the disturbance of the vertical field produced by a 4,609-foot string of casing, consisting of 600 feet of 10-inch, 3,206 feet of 6 $\frac{5}{8}$ -inch, and 1,609 feet of 4 $\frac{3}{4}$ -inch, the 6 $\frac{5}{8}$ -inch extending from the upper end of the surface casing and overlapping the 4 $\frac{3}{4}$ -inch by 206 feet. The upper end of the casing projected 4.5 feet above the ground and was provided with a cap. As before, a magnetic north-south traverse was chosen and measurements of the vertical anomaly recorded at selected positions, the magnetic system of the balance being kept at an elevation of approximately 57 centimeters below a plane through the upper end of the pipe. These observations were made in a region where the normal vertical field strength was 50,065 gammas, the mean departures from this normal value, because of the presence of the casing, being indicated in Table II.

TABLE II

<i>Distance in Feet</i>	<i>DZ in Gammas</i>
0	
5	+35,242
10	+10,674
15	+ 5,512
20	+ 2,990
30	+ 1,210
50	+ 300
100	+ 53
150	+ 11
200	0
250	0
1,000	0

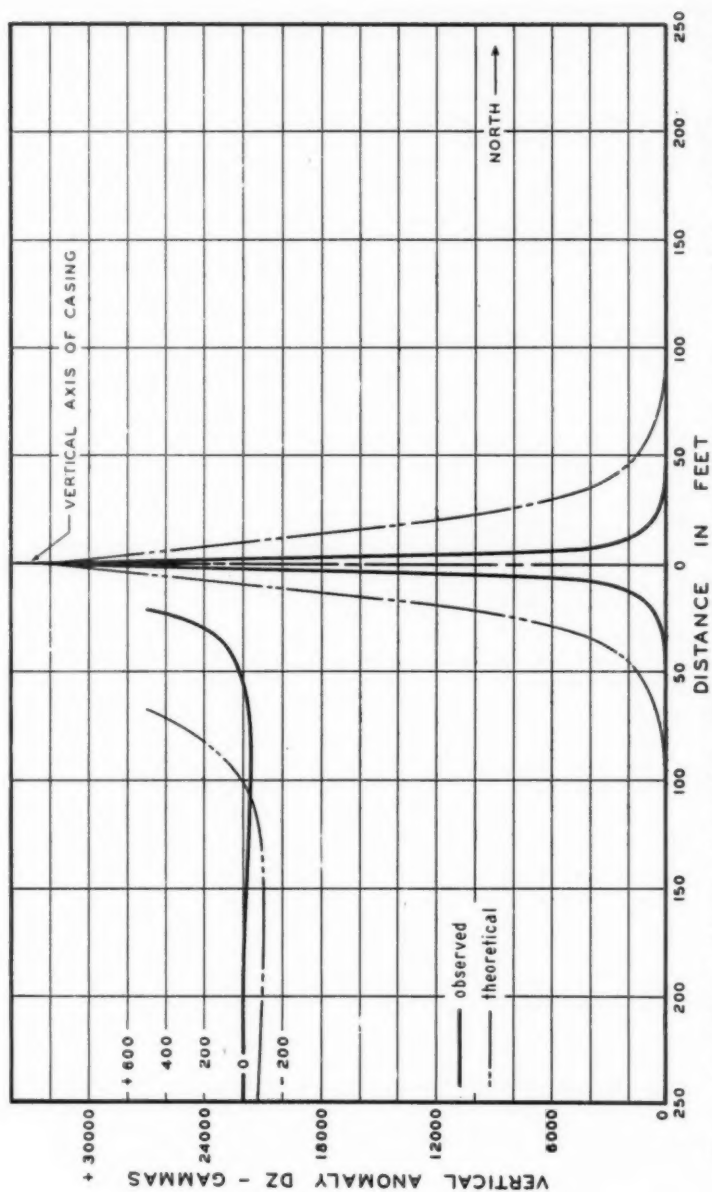


FIG. 5.—Comparison of observed and theoretical values for a magnetic north-south traverse across a 206-foot vertical string of 10-inch casing. Low values of DZ are indicated by supplementary graphs for the purpose of disclosing the negative parts of the curves.

It will be observed that no reading was obtained for the position directly above the casing. This was because of the fact that instrumental equipment was not available for measuring anomalies of this order. These data, with the exception of the last reading, are represented by the heavy curve of Figure 6, which illustrates the rapid rise of the magnetic gradient in the immediate vicinity of the casing and the disappearance of the disturbance at 200 feet. Two significant facts bear particular emphasis at this point: (1) the magnetic distortion caused by this string of casing, which is more than 22 times the length of the previously mentioned short pipe, disappears at very nearly the same radial distance; (2) there is no indication of a zone of negative anomalies as observed in the former case.

COMPARISON OF THEORETICAL AND OBSERVED DATA

For our theoretical treatment of the disturbing effect of magnetized casing we have based our discussion upon these fundamental conceptions: (1) the vertical string of casing may be regarded as a bar magnet having two *definite* magnetic poles; (2) the symmetry of the normal earth's field suffers no distortion by virtue of the presence of the magnetized pipe; (3) the direction and magnitude of the composite magnetic field near the casing head is determined by the vector composition of the secondary induced field and the normal terrestrial field. Though the validity of the last condition may be readily demonstrated, the two preceding assumptions justify further elaboration.

According to Jeans,¹ "The two ends of a magnet—or, more strictly, the two regions in which the magnetic properties are concentrated—are spoken of as the poles of the magnet." Many investigators have devoted an imposing amount of theoretical discussion and research to the study of the distribution of magnetism in bar magnets of different dimensions, and it has been determined that under some conditions a regularly magnetized bar may be treated as having two definite points, one near each end, at which the positive and negative effects may be considered concentrated. However, in any case involving the assumption of magnetic distribution for the purpose of accurately interpreting the action of a magnet at an external point, it is required, as pointed out by Gray,² that the point be removed a distance which is great in comparison with any dimension of the magnet.

¹J. H. Jeans, *The Mathematical Theory of Electricity and Magnetism* (Macmillan, New York), p. 364.

²A. Gray, *Absolute Measurements in Electricity and Magnetism* (Macmillan, New York), p. 86.

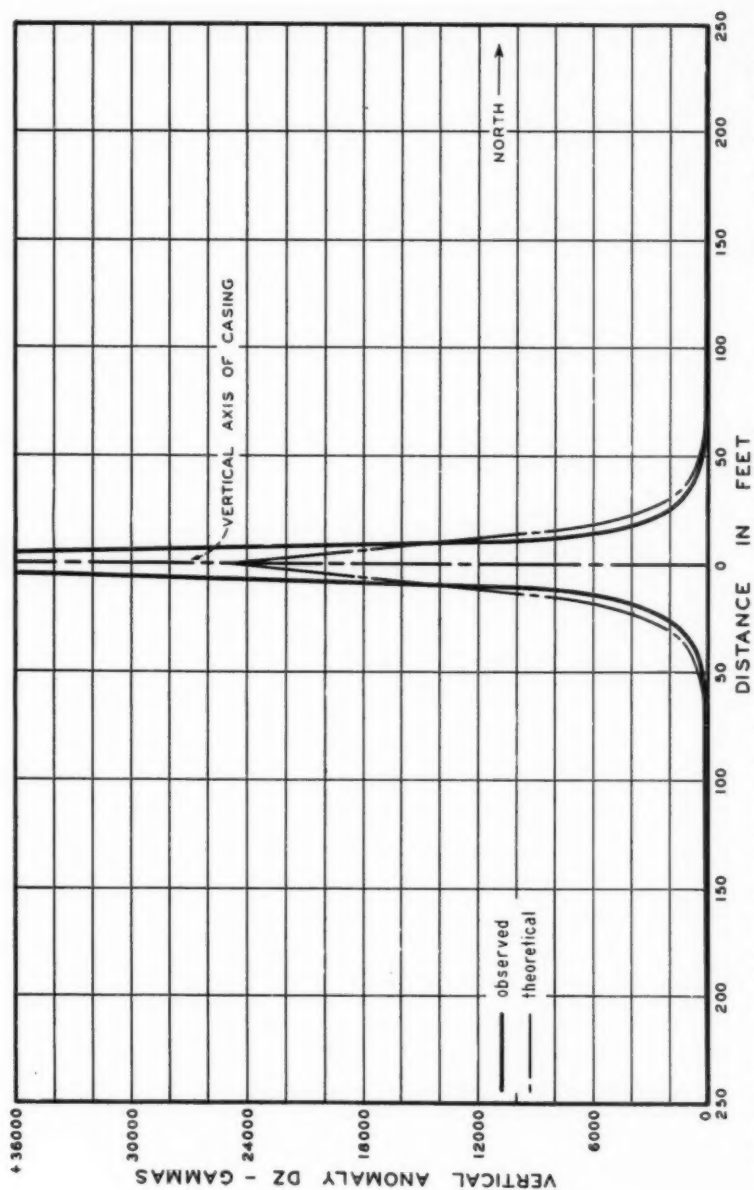


FIG. 6.—Comparison of observed and theoretical values for a magnetic north-south traverse across a 4,600-foot vertical string of casing.

As a first approximation, for the mathematical solution of the magnetic phenomena associated with the short string of casing, it was decided to regard the positive and negative effects as concentrated at the points f, e (Fig. 1), and to assume the ratio¹ of l/L to be 0.833. By reference to Figure 5, it is seen that the essential characteristics of the calculated and experimental curves are in fair conformity, equal peak values being chosen for the purpose of computing the pole strength. The divergence toward the base of the curves may be largely ascribed to our assumptions regarding the distribution of magnetism within the casing, subsequent investigation leading to the opinion that more consistent results could be obtained if the poles were considered located at the extremities of the pipe.

For the purpose of demonstrating the agreement between the theoretical and observed values when $l = L$, we place $dZ = 0$ in equation (5) and find that the calculated curve crosses the zero reference line when

$$x = \pm \sqrt{\frac{a^2 b^{\frac{3}{2}} - a^{\frac{3}{2}} b^2}{a^{\frac{3}{2}} - b^{\frac{3}{2}}}} \quad (9)$$

Also, by differentiating (5) we find dZ has a maximum value at $x = 0$, and a minimum when

$$x = \pm \sqrt{\frac{a^2 b^{\frac{3}{2}} - a^{\frac{3}{2}} b^2}{a^{\frac{3}{2}} - b^{\frac{3}{2}}}} \quad (10)$$

Substituting numerical quantities we find that dZ has a maximum value of 32,402 gammas directly over the casing, and becomes zero when $x = 54$ feet. The minimum value of -5 gammas occurs at a distance of 101 feet from the pipe and at 200 feet the effect is -3 gammas. These data are in excellent conformity with the observed quantities, with the exception of the numerical value of the negative inflection point.

So far, our comparison has been restricted to a short length of pipe in order to eliminate, as far as possible, the many uncertain factors associated with a relatively long string of casing. For this latter case, the relation between the calculated and the observed curves is illustrated in Figure 6, the required constants for the theoretical profile being found by solving simultaneously equation (5) for mean values of m and l , the corresponding anomalies and distances being obtained from the field data. The assumption was made that we may ignore the effect of the

¹This ratio is customarily supposed to lie between 0.80 and 0.875 for the ordinary type of bar magnet.

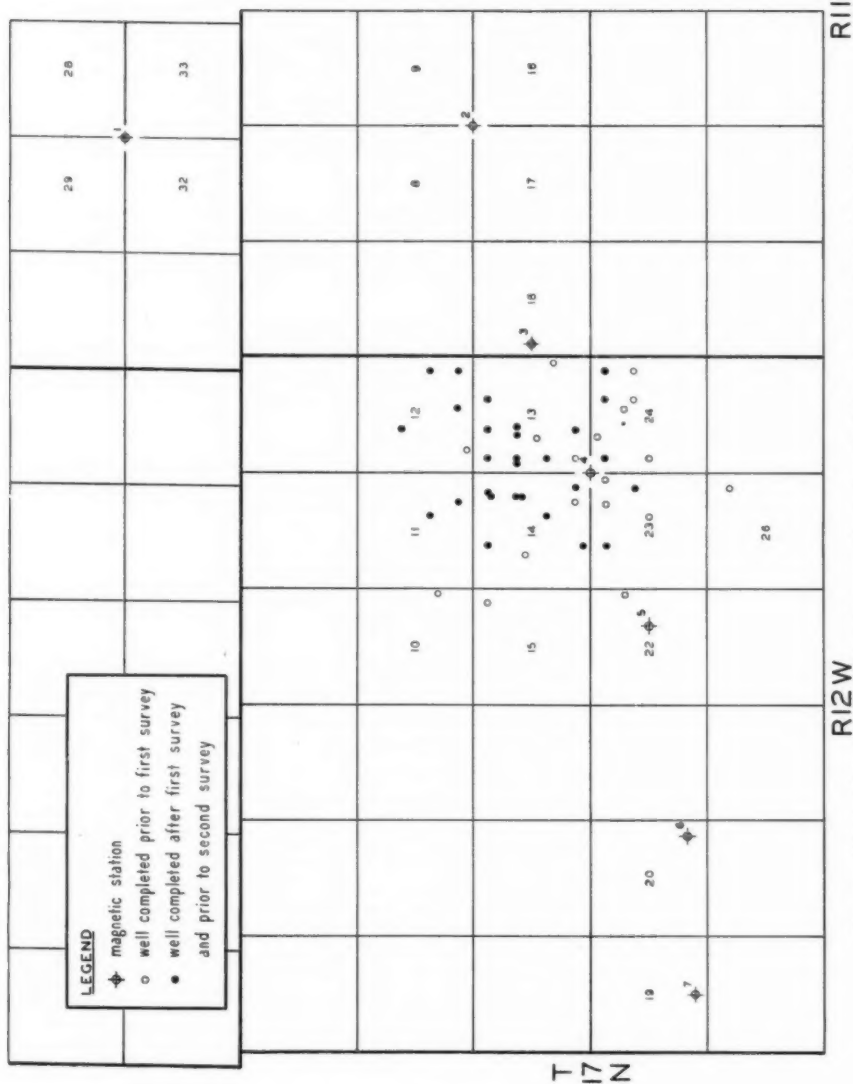


FIG. 7.—Showing locations of wells and magnetic stations in Sligo area, Bossier Parish, Louisiana.

positive magnetic pole because of its remote depth. It is seen that the lower parts of the curves are in good agreement, negative anomalies being absent in each case, and that the calculated value is decidedly too small for the position directly above the casing. The failure to observe negative values in the field supports the supposition that the effect of the lower pole may be disregarded, though it is well to mention that this same effect would be noticed had the casing extended a sufficient distance above the ground to establish the upper pole at a position above the magnetic system of the variometer. For points near the casing head the discrepancy between the curves is exaggerated because of the tremendous ratio of L to x .

It has been repeatedly argued that the pronounced magnetic "highs" associated with certain producing fields may be largely attributed to magnetized casing. As we have seen that theory and experiment are in complete accord regarding the *highly localized* nature of the disturbance traceable to this cause, we are naturally led to a consideration of the possible *areal* distortion of the magnetic elements in conjunction with producing fields. This, in fact, brings to the attention the third assumption upon which the theoretical treatment has been based, that is, the symmetry of the normal earth's field suffers no distortion by virtue of the presence of the magnetized pipe. While this interpretation is supported by its general acceptance for mathematical analysis,¹ the most conclusive evidence is that results derived in this manner may be verified by precise experiments. Only observational data regarding the possible areal effect will be considered here.

In December, 1928, at the writer's direction, a vertical intensity survey was made of the Sligo field, located in T. 17 N., R. 12 W., Bossier Parish, Louisiana. At that time there were 17 producing wells in the field, this number being increased to 45 by January, 1931, when a second series of measurements were made at the same group of stations. It is felt that this field offered exceptional opportunities for determining the possibility of an areal disturbance for the reason that only minor magnetic reflections of the subsurface relief were obtained; hence any extraneous influence would be easily recognized. The locations of the wells, together with a selected series of magnetic stations, are shown in Figure 7, and for each survey the anomalies, with respect to station No. 1, are

¹A. Gray, *op. cit.*, p. 50.

W. S. Franklin and B. MacNutt, *Advanced Theory of Electricity and Magnetism* (Macmillan, New York), p. 85.

indicated in Table III, the respective differences between the observations being included to facilitate comparison.

TABLE III

Station Number	DZ in Gammas 1928	DZ' in Gammas 1931	DZ-DZ'
1	0	0	0
2	- 4	-10	- 6
3	- 5	-12	- 7
4	-10	- 6	+ 4
5	+ 9	+ 9	0
6	+36	+16	-20
7	+32	+41	+ 9

It is seen that, with the exception of station No. 6, the variation between the surveys does not exceed the probable instrumental error, the difference at 6 being of little consequence, as this position is well removed from the area of potential disturbance. It is interesting to note, in connection with these data, that a circle having a diameter of 3 miles may be circumscribed about the field so as to enclose every well, and that the mean variation between the two series of observations, for the three stations within the circle, is only 1 gamma. Certainly, these results do not indicate that the original pattern of the vertical field has been altered by the presence of the additional wells.

CONCLUSION

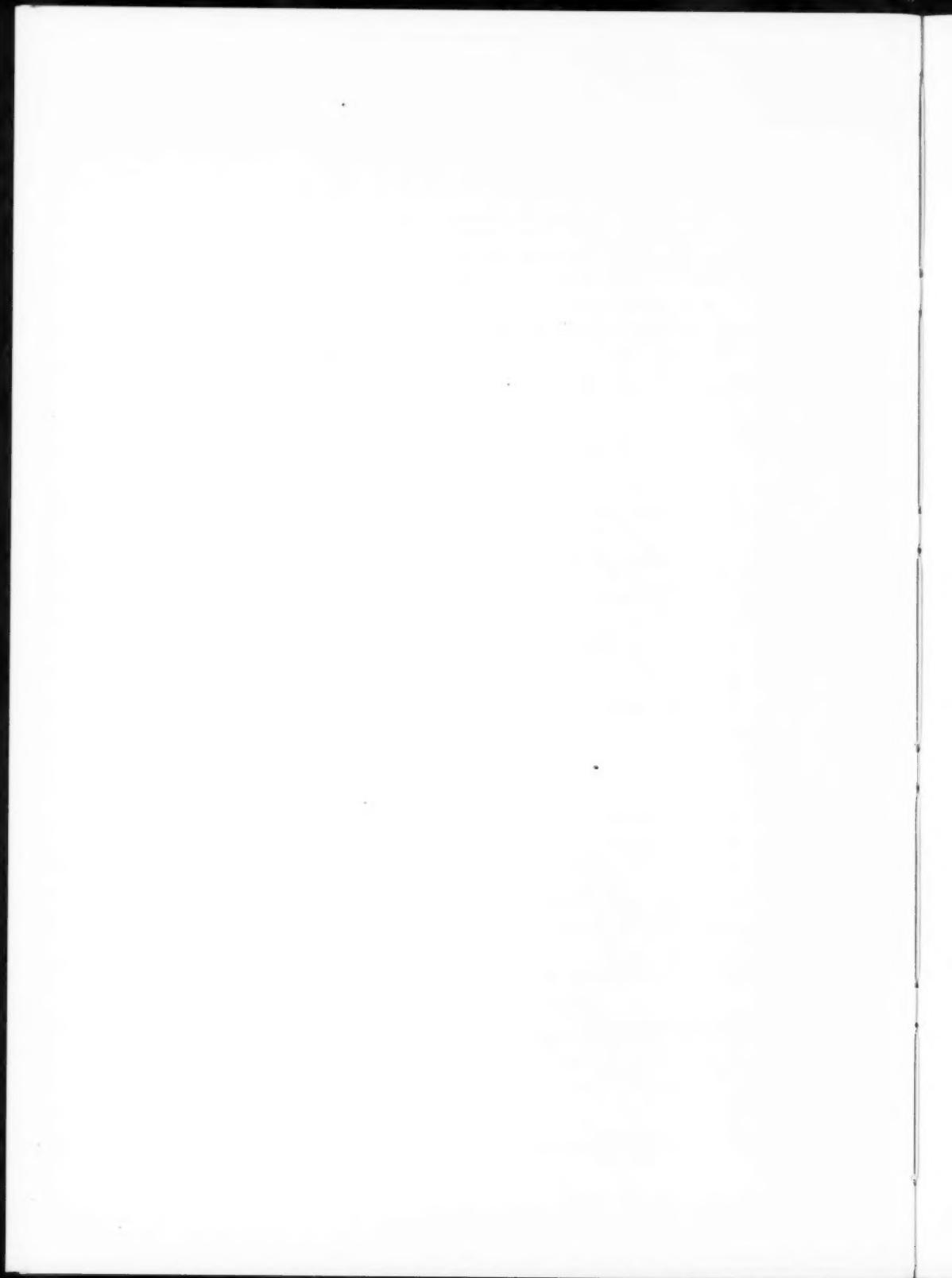
We have seen that it is possible, with our derived formulae, to delineate with fair approximation the distribution of the magnetic elements within the surficial zone that surrounds an element of magnetized casing. These equations were not developed for the purpose of determining the appropriate correction belonging to an effected observation, but rather to explain and amplify our experimental evidence relating to the phenomena. By a more elaborate process we might define the observed effects with precise fidelity, although it is well to remember that the geophysicist is primarily interested in the attenuation of the disturbance and for this purpose the present derivations are entirely adequate.

In concluding, the writer wishes to summarize the following pertinent deductions.

1. The magnetic disturbance caused by an isolated string of magnetized casing is of a highly localized character.
2. The maximum effect, which occurs in the immediate proximity of the casing head, varies as the physical proportions of the pipe, increasing very nearly as the cross-sectional area of metal at the casing head.

3. From the present investigation it seems that the anomalous vertical effect disappears at a radial distance of approximately 200 feet from the casing head, and it is the writer's opinion that, for any commercial-size casing, this disturbance may be ignored at a distance of 500 feet.

4. In producing fields there appears to be no areal deformation of the vertical element, aside from the influence within the concentric zones surrounding the casing heads.



BRUNTON COMPASS ATTACHMENT FOR MEASUREMENT OF HORIZONTAL MAGNETIC INTENSITY¹

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ABSTRACT

Utilizing the Brunton compass in common use by geologists, an attachment has been devised making it possible to measure the horizontal intensity of the earth's field. The operation of the instrument, the theory and derivation of equations, and the results of several surveys with the instrument are presented.

INTRODUCTION

As the Brunton compass is in almost universal use by geologists and engineers, an attachment which enlarges the usefulness of the compass is important. The attachment described herein is designed to measure the absolute horizontal intensity of the earth's magnetic field with sufficient accuracy to be of aid in some classes of geophysical work. The instrument is not intended for close or accurate magnetic investigations, but should be used where the anomalies exceed 250 gammas. The accuracy of the instrument in magnetic investigations is comparable with the accuracy obtained by the Brunton in traverse work.

CONSTRUCTION OF INSTRUMENT

The attachment consists of the compass holder and an auxiliary magnet arm.

The compass holder is constructed of non-magnetic metal, with slots which fit corresponding projections on the bottom of the Brunton compass. Two clamping screws prevent the compass from moving or falling off the compass holder when the attachment is in use.

The auxiliary and detachable magnet arm is graduated in millimeters and carries a magnet holder with a vernier reading device. The magnet holder is moved along the auxiliary arm by means of an adjustable rack and pinion. The auxiliary magnet arm makes an angle of 120° (measured in a clockwise direction) from the north index of the compass box. In

¹Read before the Association at the San Antonio meeting, March 21, 1931. Manuscript received, March 14, 1931.

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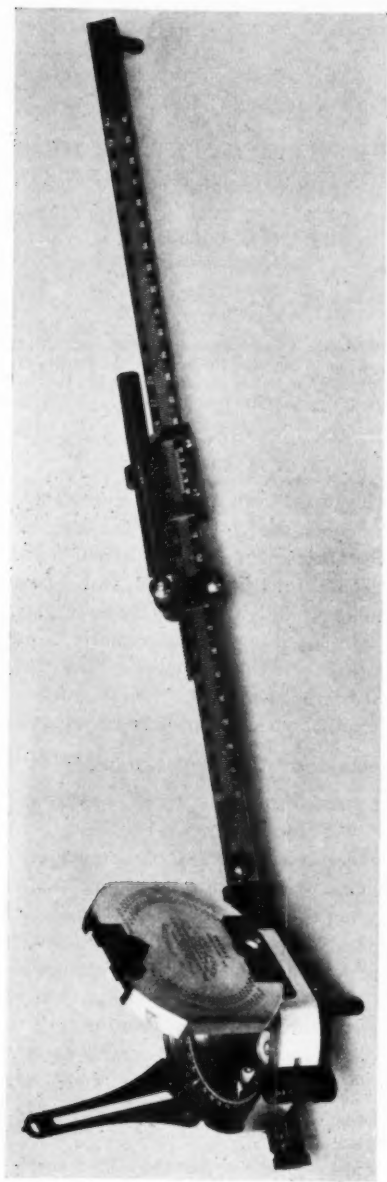


FIG. 1.—Brunton compass attachment for measurement of horizontal magnetic intensity.

using the instrument as a magnetometer, zero of the graduated circle is set exactly beneath the north index of the compass box.

OPERATION OF INSTRUMENT

The instrument may be used on a flat board or table or on an 18 × 24-inch planetable, or it may be mounted on a special tripod. The writer has found the use of the 18 × 24-inch planetable the most satisfactory. As the planetable is usually part of the geologist's equipment and if properly constructed is made of non-magnetic material, its use is recommended.

The steps of setting up the instrument and determination of horizontal intensity are as follows.

1. Place the ring on the base of the Brunton compass in the circle on the compass holder so that the projecting screw on the base in the northeast quadrant fits into the locating hole. Then clamp the compass firmly in the holder by means of the clamps and clamp screws engaging the slots on either side of the compass box.
2. Attach the auxiliary arm to the compass holder and clamp it by means of the clamping screw, move the magnet carrier with the rack and pinion into the approximate working position, and clamp the rack to the arm with the lower screw.
3. Level and approximately orient the instrument on the planetable or tripod with the aid of the level bubbles in the compass.
4. With the zero line of the graduated circle opposite the index, turn the whole instrument in a horizontal plane until the north end of the needle points exactly to the north point on the graduated circle. A small reading glass (containing no magnetic material) is of assistance. The auxiliary magnet should be at a distance of about 20 feet so that it can have no possible effect on the needle.
5. After orienting as in step 4 with the needle at rest, place the auxiliary magnet in the magnet holder with the south-seeking end of the magnet toward the compass. This should be done carefully so as not to disturb the level or orientation of the instrument.
6. Move the magnet carrier (with magnet in place) by means of the rack-and-pinion device until the north end of the needle is exactly at the 30° mark. In this position the needle is perpendicular to the axis of the auxiliary magnet and the magnet is in position known as the first position of gauss. It is suggested that the operator hold one hand on the auxiliary arm between the compass and the magnet while moving the magnet holder so that the orientation shall not be disturbed.

7. Read the distance, r , on the auxiliary magnet arm by means of the vernier to the nearest one hundredth of a centimeter.

At the conclusion of an observation, the compass box may be closed and the instrument may be carried already set up to the next station.

THEORY

The general theory of such a set-up can be obtained from any good book of physics.¹

The equation which applies to the instrument when used as above is as follows:

$$H = \frac{4M}{r^3} \left(\frac{1}{1 - \frac{L^2}{2r^2} + \frac{L^4}{16r^4}} \right) \quad (1)$$

where H is the horizontal intensity at the desired point; M is the magnetic moment of the auxiliary magnet; r is the distance between the center of the needle and the center of the magnet; and L is the length of the auxiliary magnet.

If the values of r are large in comparison with L , equation (1) reduces to

$$H = \frac{4M}{r^3} \quad (2)$$

For anomalies of fair magnitude, equation (2) is sufficiently accurate.

As in any survey L and M are constant, a table or graph of the value of H for any value of r can be computed and used where absolute values are desired. The magnetic unit must, of course, first be determined by any of the customary methods.

When effects, such as temperature and diurnal variation, are less than the observational errors of the instrument, they may be neglected.

PROBLEMS TO WHICH APPLICABLE

With the vernier arrangement it is possible to read r to the tenth of a millimeter. With the strength of magnet commonly used it would be impossible to obtain the intensity closer than 25 gammas. Repeated set-ups by a competent observer at the same station checked within 0.025 centimeters of the mean value, which is equivalent to a departure

¹William Watson, *Text Book of Physics* (Longmans, Green and Company, 1919).

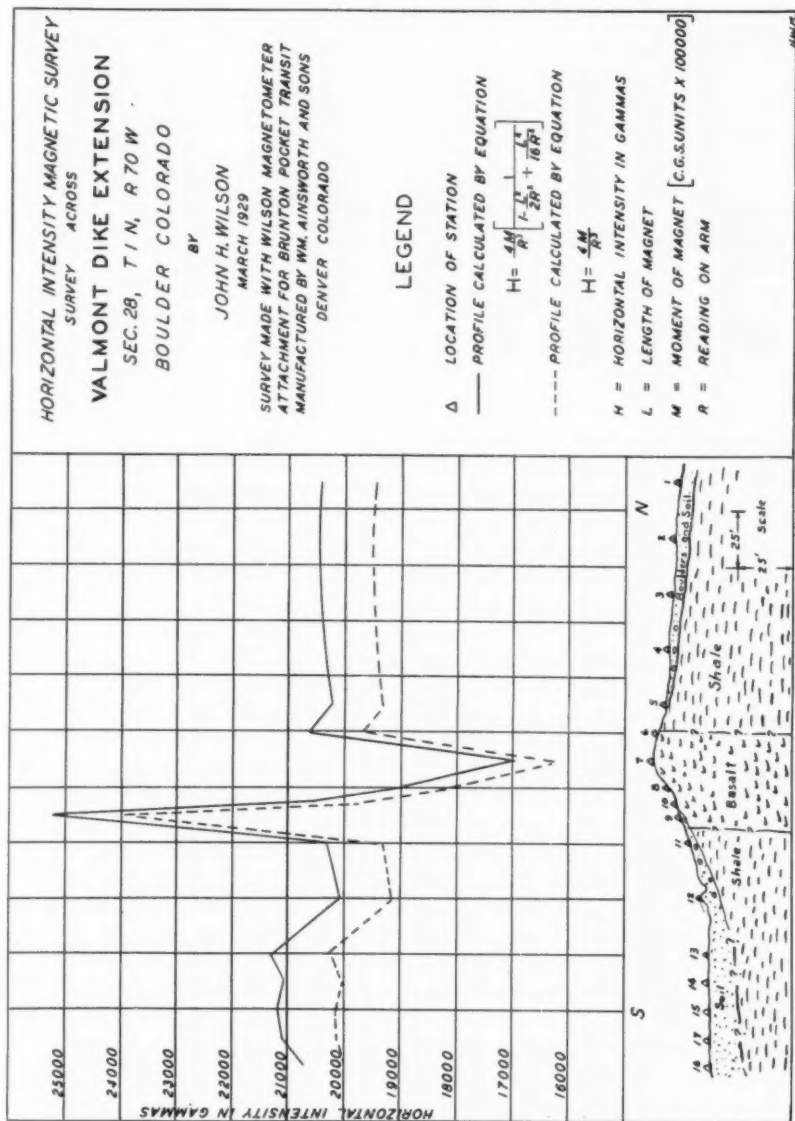


FIG. 2.—Results of survey with instrument near Boulder, Colorado.

of about 70 gammas from the mean. In practice it has been found that the instrument does not give satisfactory results on anomalies of less than 250 or 300 gammas.

The instrument is, therefore, applicable to investigation of larger anomalies. It gives fair results over the larger anomalies found in oil work, over basic dikes, and over magnetic ore bodies.

The instrument is so designed as to work in a range from 5,000 to 100,000 gammas absolute horizontal intensity. Without use of magnets of different strength, the instrument could not be used in regions where the intensity fell below 5,000 gammas or rose above 100,000 gammas.

It is not recommended that petroleum geologists use the instrument for regular reconnaissance work. It is best adapted to horizontal intensity work on large vertical anomalies which have already been located and to the investigation of igneous intrusions.

Mining geologists should find the instrument of aid in the tracing of some types of dikes, the limits of intrusive bodies, and the investigation of iron ore deposits. However, the instrument can not be expected to work on sulphide ore bodies not associated with magnetic minerals.

The instrument is well adapted to illustrate methods of measuring the intensity of magnetic fields, the moments of magnets, magnetic couples, and other magnetic phenomena. It would be of considerable use to a teaching physicist.

SOME RESULTS OBTAINED

In Figure 2 are shown the results of a survey across a small dike of basaltic rock near Boulder, Colorado. The dike could readily be traced with this instrument. Calculation of results by equations (1) and (2) are shown. It may be observed that for location work the simplified equation could be used satisfactorily.

In Figure 3 are shown the results of a horizontal intensity survey across the Mankato "high" in Jewell County, Kansas, which had a vertical anomaly of approximately 900 gammas. Below the profiles are shown the vectors calculated from the horizontal and vertical anomalies. It should be noticed that the vectors are calculated in the magnetic meridian, whereas the section was surveyed in true north and south directions. The results indicate that survey with this instrument is satisfactory on anomalies of this size and that they may give valuable information as to whether polarization is present, and if so, whether the magnetic axis is vertical or inclined, and whether the magnetic axis of the disturbing body should be regarded as of finite or infinite length.

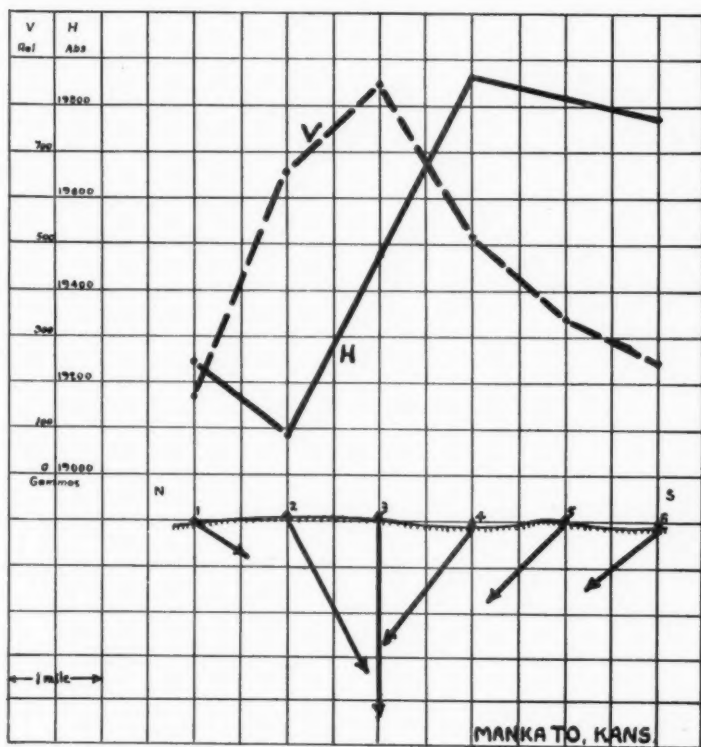
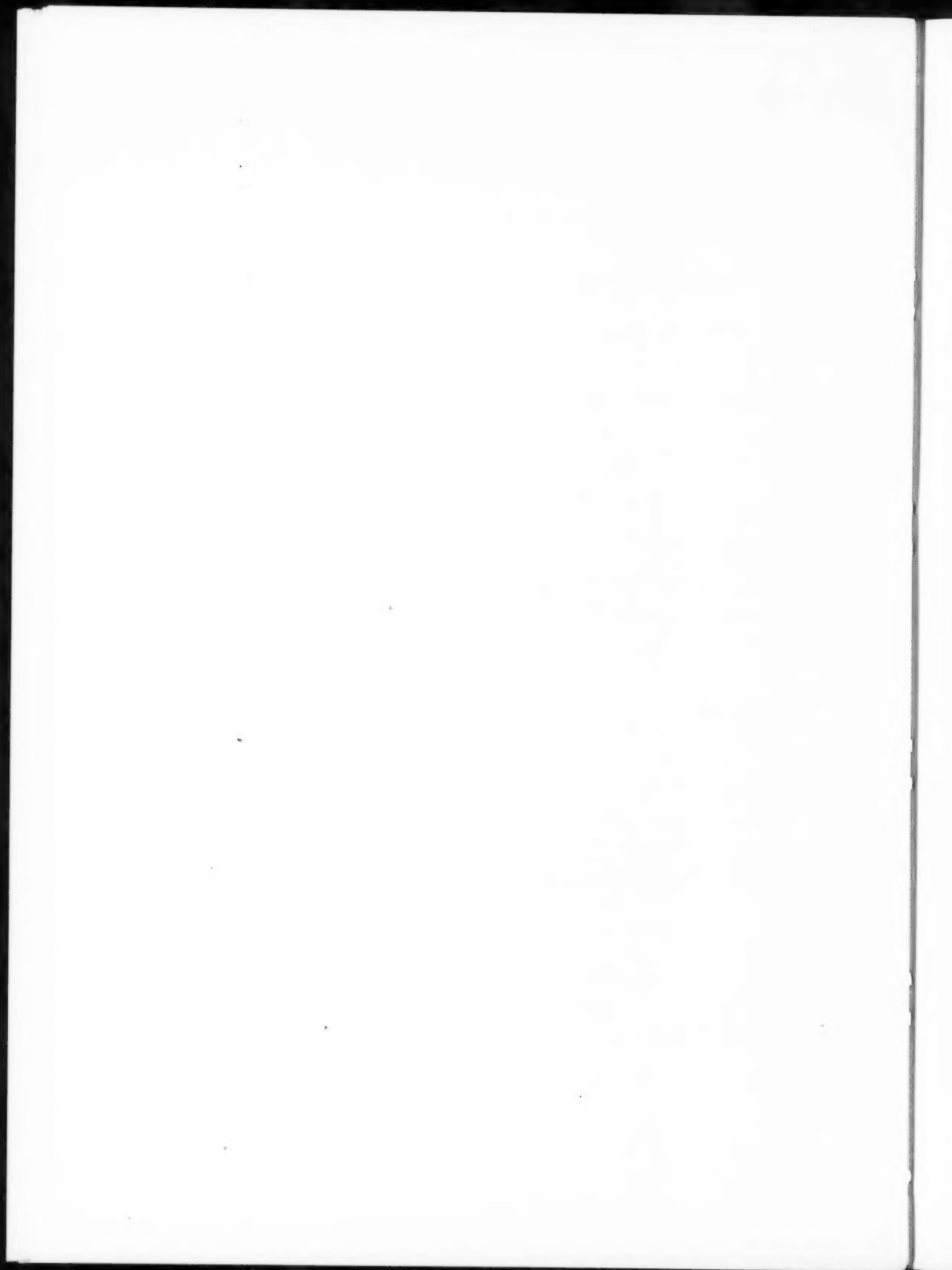


FIG. 3.—Profiles across "high" near Mankato, Kansas. Station 1 is at NE. cor. Sec. 1, T. 3 S., R. 9 W. Vertical intensity obtained with Schmidt magnetometer; horizontal intensity, with Brunton compass attachment.

By triangulation procedure, depth to the disturbing mass could be calculated under some conditions.



REVIEWS AND NEW PUBLICATIONS

Principles of Structural Geology. By CHARLES MERRICK NEVIN. (John Wiley & Sons, Inc., New York, 1931). 303 pp. with index and illustrations. Price, \$3.50.

Nevin's *Structural Geology* is a text designed, seemingly, for beginning students in structural geology. Its general plan is indicated by the following list of chapter headings: Physical Properties of Rocks; Stress and Strain Relations; Flexures; Faults; Joints; Cleavage; Structures in Unconsolidated Sediments; Reflection of Rock Structure in the Topography; Some Facts, Inferences, and Hypotheses Regarding the Earth; Continents and Ocean Basins; Mountain Systems.

In addition to the topics usually treated under the headings listed, the following new features deserve special mention. In the chapter on folding is a brief discussion of the effect of regional dip on the surface expression of small folds, together with diagrams illustrating a graphical method for calculating the original dip which can be used also for determining the effect of convergence on the shape of folds at depth. Compaction of sediments and the structural effects of differential compaction receive extended treatment in the chapter on unconsolidated sediments which incorporates several recent papers on those subjects. The inclusion of the chapter on reflection of rock structures in the topography seems to the reviewer to be a very commendable innovation in texts on structural geology.

The chapter on joints serves to awaken a lively interest in the subject and leaves the reader with a wholesome feeling that much remains to be learned about them.

The last three chapters, dealing with the broader problems of earth structure and of mountain building, furnish interesting and stimulating reading. The author has outlined the various theories, with comments on their strong and weak points. That the theory of continental drifting is not lightly to be dismissed is an evident belief of the author. These three chapters, as a whole, leave the reader with a clear understanding of the fact that many of the problems connected with the genesis of mountains are still unsolved.

As in any new book, a few mistakes and several places where clarity of presentation might be improved can be mentioned. The reviewer feels that the expression "three rectangular planes" (p. 13, 2d line) should not have been perpetuated, even as a quotation. On p. 19 the axes of stress and strain having intermediate values are called "*mean axis of stress*" and "*mean axis of strain*" (italics are the reviewer's). This is confusing because, to the general reader, and doubtless to the student, *mean* signifies *average*. A similar criticism applies to the use of the word *normal* in "normal stress" (p. 24, 12th line from last) and "normal horizontal separation" (p. 80, 11th line from last). Use of such terms in an entirely different meaning from that in common use (even if correct

in geometrical language) is bound to lead to confusion. Imagine a student's state of mind on reading on p. 80 of "normal horizontal separation" and on p. 82 of "Normal and Reverse Faults." Other examples (p. 89, line 26) of the confusing use of the word *normal* might be cited.

With reference to the discussion of jointing (pp. 150-52), the reviewer feels that a clear demonstration that "vertical joint systems are the result of regional stresses on brittle rocks under conditions where lateral relief is easier than upward relief" has yet to be made.

On account of the analytical treatment of controversial subjects, particularly in the concluding chapters, the mature geologist will find this a useful addition to his library. A decided emphasis on structural problems encountered in oil work is noticeable.

JOHN L. RICH

UNIVERSITY OF CINCINNATI
CINCINNATI, OHIO
OCTOBER 13, 1931

RECENT PUBLICATIONS

CALIFORNIA

Mining in California (Division of Mines, San Francisco, April, 1931), contains the following articles: "Stratigraphic Significance of the Kreyenhagen Shale of California," by Olaf P. Jenkins; "Diatoms and Silicoflagellates of the Kreyenhagen Shale," by G. D. Hanna; and "Foraminifera of the Kreyenhagen Shale," by C. C. Church.

"Geology of the Eastern Part of the Santa Monica Mountains, Los Angeles County, California," by H. W. Hoots. *U. S. Geol. Survey Prof. Paper 165-C* (Supt. Documents, Washington, D. C.), pp. i-ii, 83-134, Pls. 16-34 (including 3 maps), Figs. 7-8. Price, \$0.75.

GENERAL

"La question des eaux dans les gisements de pétrole" (Problem of Water in Oil-Bearing Beds), by H. de Cizancourt. *Annales de l'Office National des Combustibles Liquides* (Paris), Vol. 6, No. 2 (March-April, 1931), pp. 195-224; 6 figs.

"Erdöl und rezente Faulschlamme" (Petroleum and Recent Muds), by A. F. von Stahl. *Petrol. Zeit.* (Berlin), Vol. 27, No. 35 (August 26, 1931), p. 629. Refers to work of Trask as published in this *Bulletin*.

Oil Well Completion and Operation, by H. C. George. (Univ. Oklahoma Press, Norman, Oklahoma, 1931.) 234 pp., 52 figs. 7 $\frac{3}{4}$ × 10 $\frac{3}{4}$ inches. Cloth. Price, postpaid, \$3.15.

"El 'ABC' de la geología del petróleo" (Introduction to Petroleum Geology), by Enrique Fossa-Mancini. *De Boletín de Informaciones Petrolíferas* (Buenos Aires, Argentina), Vol. 8, Nos. 82-83 (June-July, 1931). 68 pp., 25 figs., including oil and gas map of Argentina.

The United States Geological Survey has published limited editions of charts showing tentative correlations of geological formations in each of the

following states: California, Colorado, Connecticut, Indiana, Iowa, Kentucky, Louisiana, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Jersey, New York, Ohio, Oklahoma, Pennsylvania, Rhode Island, Tennessee, Texas, Virginia, West Virginia, Wisconsin. The supply of the Wyoming chart is exhausted. North Dakota and South Dakota charts will soon be ready for distribution. As long as the small supplies of these correlation charts last, copies may be obtained free on application to the director of the Survey. Anyone desiring the complete set should request that his name be added to the mailing list for them.

A New Geologic Index of United States Geological Survey Publications, by George H. Albertson. Publications tabulated numerically according to latitude and longitude as shown on accompanying maps. More than 400 pages. (Geological Publishing Company, 508 Colorado Building, Denver, Colorado.) Price with maps, prepaid, \$10.00.

Petroleum in the United States and Possessions, by Ralph Arnold and William J. Kemnitzner. (Harper and Brothers, New York and London, 1931.) 1052 pp., 91 tables, 30 illus. Price, \$16.00.

GEOPHYSICS

"Règles pratiques pour déterminer les constantes d'un magnétomètre" (Practical Rules for Determining the Constants of a Magnetometer), by C. L. Alexanian. *Annales de l'Office National des Combustibles Liquides* (Paris), Vol. 6, No. 2 (March-April, 1931), pp. 261-67.

"A Selected List of Books and References on Geophysical Prospecting," C. A. Heiland and Dart Wantland. *Colorado School of Mines Quart.* (Golden), Vol. 26, No. 3 (July, 1931). Approximately 200 references primarily for undergraduates. 24 pp. Price, \$0.50.

Handbuch der Geophysik (Handbook of Geophysics), Vol. 2, Pt. 1 (1931), edited by B. Gutenberg. Contains "Abkühlung und Temperatur der Erde" (Cooling and Earth Temperature), by B. Gutenberg; "Chemie der Erde" (Chemistry of the Earth), by G. Berg; "Alter der Erde und geologische Zeitalter" (Age of the Earth and Geological Time), by A. Born; and "Der physikalische Aufbau der Erde" (Physical Structure of the Earth), by B. Gutenberg. (Borntraeger Brothers, Berlin.) 564 pp., 183 illus. Price \$24.50; price to subscribers to the complete Handbook, \$16.40 (special to A. A. P. G. members, \$12.30).

Handbuch der Geophysik, Vol. 6, Pt. 1 (1931). Contains "Eigenschaften der Gesteine (Properties of Rocks), by H. Reich; "Die elektrischen Aufschlussmethoden" (Electrical Exploration Methods), by H. Hunkel; "Theorie der gravimetrischen Aufschlussmethoden" (Theory of Gravimetric Exploration Methods), by E. A. Ansal; "Instrumente der gravimetrischen Aufschlussmethoden" (Instruments of Gravimetric Exploration Methods), by O. Meisser. (Borntraeger Brothers, Berlin.) 312 pp., 134 illus. Price, \$15.00; price to subscribers to complete Handbook, \$10.00 (special to A. A. P. G. members, \$7.50).

KENTUCKY

"The Building of Kentucky," by W. H. Twenhofel; "Mineral Resources of the Ashland, Kentucky, Region," by W. C. Burroughs; "A Reconnaissance

Survey of the Geology of Northern Hardin County," by A. H. Sutton; and "A Reconnaissance Report on the Geology of McLean County," by L. C. Robinson. *Kentucky Geol. Survey Vol. 37* (1931). 68 figs. and pls. (Frankfort, Kentucky.) Cloth. Price, \$1.25.

NEW MEXICO

Oil and Gas Map of New Mexico (1931), by Dean E. Winchester. (State Bur. Mines and Mineral Resources, New Mexico School of Mines, Socorro, New Mexico.) U. S. Geol. Survey base in black and white; oil and gas data in red. Scale 1 inch = 16 miles. Map published in advance of report to be ready in 1932. Sheet, $25\frac{1}{2} \times 27\frac{3}{4}$ inches. Price, paper, \$1.00; cloth-backed, \$1.50.

OHIO

"Geology and Mineral Resources of the Cleveland District, Ohio," by H. P. Cushing, Frank Leverett, and F. R. Van Horn. *U. S. Geol. Survey Bull. 818* (Supt. Documents, Washington, D. C., July, 1931). 138 pp., 23 pls. (including 3 maps), 11 figs. Price, \$0.65.

OKLAHOMA AND ARKANSAS

Guide Book of the Fifth Annual Field Conference of the Kansas Geological Society (September, 1931). 97 pp., 23 maps, photographs, correlation charts, and diagrams; 9×11 inches. Accompanied by *Geologic Cross Section of the Central United States* (1,950 miles), prepared by six authorities on Mid-Continent stratigraphy. Scale, 1 inch = 20 miles horizontal, and 1 inch = 400 feet vertical; 54×110 inches. (Kansas Geological Society, 412 Union National Bank Building, Wichita, Kansas.) Price complete, \$8.00.

"The Stratigraphy and Physical Characteristics of the Simpson Group," by Charles E. Decker and Clifford A. Merritt. *Oklahoma Geol. Survey Bull. 55* (1931). 112 pp., 2 figs., 15 pls.

TEXAS

The University of Texas Bureau of Economic Geology at Austin announces the following new publications.

"Contributions to Geology, 1931": (a) "Erratics in the Pennsylvanian of Texas," by E. H. Sellards; (b) "Some Major Structural Features of West Texas," by H. P. Bybee; (c) "New Early Fusulinids from Texas," by Norman L. Thomas; (d) "Some Upper Cretaceous Ammonites in Western Texas," by W. S. Adkins; (e) "The Lower Claiborne on the Brazos River, Texas," by B. Coleman Renick and H. B. Stenzel; (f) "Some Cretaceous Foraminifera in Texas," by Helen Jeanne Plummer. *Bull. 3101*. 207 pp., 12 figs., 15 pls. Paper cover, \$1.00; cloth, \$1.75.

"The Geology of Grayson County, Texas," by Fred M. Bullard. *Bull. 3125*. 72 pp. and map. Price, \$0.50.

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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ANNOUNCEMENT

GEOLOGICAL SOCIETY OF AMERICA AND THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS MEETING, TULSA, OKLAHOMA, DECEMBER 28, 1931, TO JANUARY 4, 1932

Headquarters and registration at Mayo Hotel.

Scientific sessions, December 29 to 31, inclusive, Mayo Hotel. Presidential address, evening of December 29, Central High School Auditorium, followed

by smoker and dance, 16th floor, Mayo Hotel. Annual banquet, December 30, Crystal Ballroom, Mayo Hotel. Ample hotel accommodations will be available at reasonable prices.

Reduced railroad rates have been granted by all passenger associations. Return certificates will be issued to each Association member, authorizing either one of two routes: (1) going and returning by way of the same route at the rate of fare and a half for the round trip; (2) going by one authorized route at the rate of 75 per cent of one way fare from point of departure to destination (Tulsa) and returning by any other authorized route at the rate of 75 per cent of one way fare for the return route. Both tickets good for thirty days in addition to the date of sale. Tickets will be on sale December 24-30. Information with respect to stop-overs and other details should be obtained by members from local ticket agents.

Several field trips are planned as follows.

December 28—Oklahoma City and return by train, leaving Tulsa at 7:45 A. M. and returning the same evening. The other trip to Spavinaw and the Ozarks by motor, leaving Tulsa not later than 8:30 A. M. and returning the same evening.

Those making the field trip to the Arbuckle Mountains will leave Tulsa by train the night of December 31 and will leave Ada, Oklahoma, January 1, spending the night at Ardmore. January 2 will be spent in the Ardmore basin, after which the party will divide, some going to the Wichita Mountains and others to the Ouachita Mountains. Those going to the Wichita Mountains will return by way of Oklahoma City to Tulsa, January 4, and those going to the Ouachita Mountains will spend the first day, Antlers to Johns Valley and return; the second day, Antlers to McAlester and Tulsa.

All Association members are cordially invited and urged to attend this meeting. For further information, write Frank R. Clark, Box 2064, Tulsa, Oklahoma.

CORRECTION

PERMO-CARBONIFEROUS OROGENY IN SOUTH-CENTRAL UNITED STATES

In W. A. J. M. van der Gracht's article in the September *Bulletin* (page 1043), reference was made to the occurrence of *Schwagerina* in beds of Cisco age, credit for the information being given to the undersigned. Before final examination of the evidence was made, the statement was printed. The evidence is considered unauthoritative until further substantiation is secured from unquestionable localities.

BRUCE HARLTON
F. A. BUSH

TULSA, OKLAHOMA
October 7, 1931

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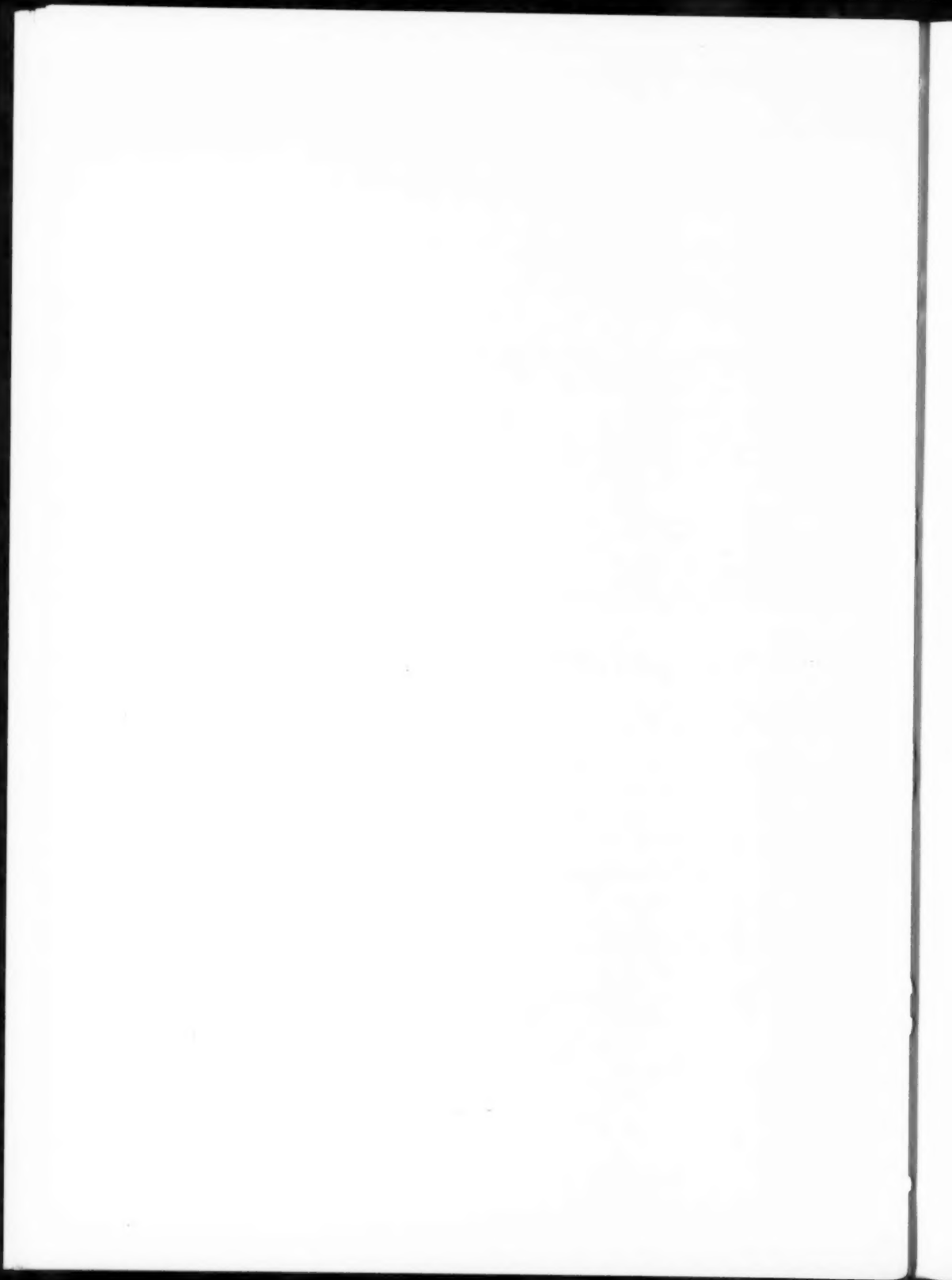
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AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

EMPLOYMENT

The Association maintains an employment service at headquarters under the supervision of the business manager.

This service is available to members and associates who desire new positions and to companies and others who desire Association members and associates as employees. All requests and information are handled confidentially and gratuitously.

To make this service of maximum value, all members and associates in the Association are requested to cooperate by notifying the business manager of openings available.

VIRGIL R. D. KIRKHAM, geologist, Saginaw, Michigan, has a paper entitled "Igneous Geology of Southwestern Idaho" in the August-September issue of *The Journal of Geology*.

H. T. MORLEY, geologist, has been made division manager of the exploration department in the state of Texas for the Stanolind Oil and Gas Company.

NORMAN HARDY, formerly with the Standard Oil Company, Los Angeles, is now with the Nederlandsche Pacific Petroleum Maatschappij, Batavia, Java, Dutch East Indies.

DANA HOGAN, manager of lands for the Petroleum Securities Company and vice president and manager of the Los Nietos Producing and Refining Company, is giving up active service with the Doheny organizations after 19 years. He intends spending an indefinite time in Europe.

WILLIAM F. LOWE, geologist, Tulsa, Oklahoma, has an article entitled "Production Methods and Problems in East Texas" in the September issue of *International Petroleum Technology*.

V. E. COTTINGHAM, who has been associated with Glenn O. Briscoe in geological consulting work in West Texas with headquarters at San Angelo, has been appointed a deputy supervisor of the oil and gas division of the Texas Railroad Commission, and assigned to the East Texas field.

VINCENT W. VANDIVER, in charge of the land department for the Standard Oil Company of Venezuela, has been transferred from Maracaibo to the new headquarters for the company in eastern Venezuela. His new address is Box 284, (Caripito), Port of Spain, Trinidad.

RICHARD A. JONES, 1011 San Pedro Avenue, San Antonio, Texas, has an article "Surface and Subsurface Character of Edwards Limestone" in the September 11 issue of *The Oil Weekly*.

E. L. JONES, district geologist for the Shell Petroleum Corporation in San Angelo, Texas, has resigned his position and has moved to California.

The West Texas Geological Society met at San Angelo, Texas, September 12, 1931. R. B. WHITEHEAD, chairman of the Dallas Petroleum Geologists, spoke on "The East Texas Oil Field."

At a meeting of the San Angelo Conglomerates on September 1, H. A. HEMPHILL, of the University Land Survey, gave a brief discussion of the effects of the earthquake near Valentine, Texas.

E. C. EDWARDS has resigned his position as geologist for the Prairie Oil and Gas Company in California and will continue his studies toward a doctor's degree at California School of Technology this year.

GEORGE A. KROENLEIN, formerly consulting geologist of San Angelo and Del Rio, has organized the West Texas Chemical Company to treat buildings with chemicals for the eradication of termites.

WILLIAM J. NOLTE, of the Stanolind Oil and Gas Company, has headquarters in the Medical Arts Building at Fort Worth, Texas. He was formerly at Wichita Falls.

G. S. DILLE, formerly engaged in field work for The Texas Company in Oklahoma and Kansas, is now located at the Tulsa office doing micropaleontological work.

WALLACE RALSTON, geologist for the Sun Oil Company, has been transferred from San Angelo to Tyler, Texas. His address is Box 807.

HERBERT C. G. VINCENT, geologist for the Shell Oil Company, Los Angeles, has been transferred to Sarawak Oilfields, Limited, Miri, Sarawak, via Singapore.

WALTER E. HOPPER has resigned as president and a director of The Southern States Company, Inc., of Shreveport, Louisiana, and is no longer connected with the company.

H. FOSTER BAIN, secretary of the American Institute of Mining and Metallurgical Engineers since 1925, resigned on November 1, 1931, to go with the Copper and Brass Research Association. A. B. PARSONS, assistant secretary of the Institute, succeeds Mr. Bain as secretary.

W. A. J. M. VAN WATERSCHOOT VAN DER GRACHT will be at 1742 N St., N. W., Washington D. C., this winter.



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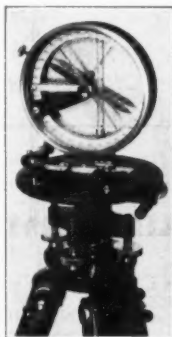
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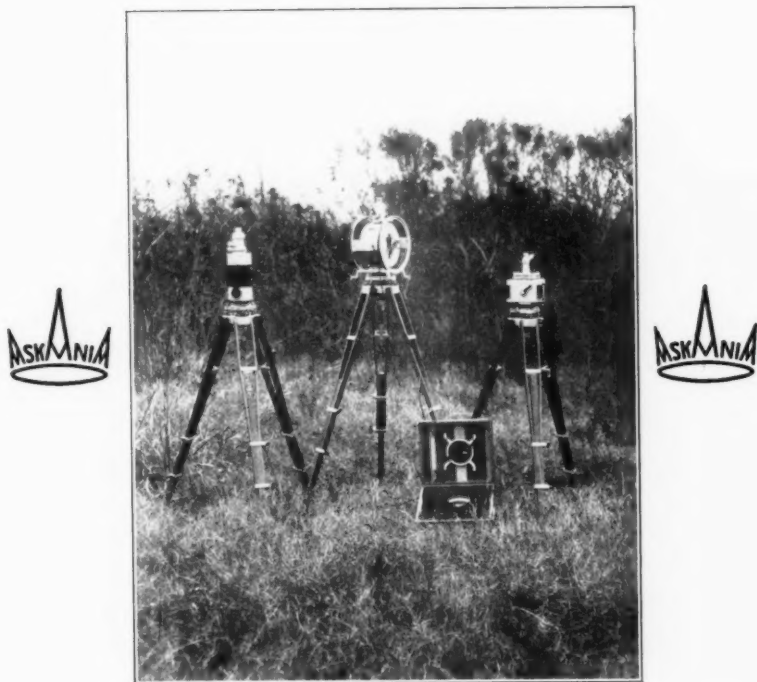
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